MODELING GROWTH OF PIGS REARED TO HEAVY WEIGHTS

BY

CALEB MICHAEL SHULL

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Animal Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2013

Urbana, Illinois

Doctoral Committee:

Professor Mike Ellis, Chair
Professor Floyd McKeith
Professor Donald Bullock
Dr. Beau Peterson, The Maschhoffs, LLC

ABSTRACT

A series of studies were conducted to determine the relationship between live weight and growth performance measures of pigs reared to heavy weights in commercial facilities and to evaluate different methods of modeling these relationships. The first study was designed to develop growth curves of live animal growth performance and ultrasound measures for barrows and gilts from weaning to a pen mean live weight of 167.5 ± 3.30 kg. The results of this study suggested that instantaneous ADG peaked at 78 and 77 kg live weight for barrows and gilts, respectively, and decreased thereafter, instantaneous ADFI peaked at 115 and 121 kg for barrows and gilts, respectively, and decreased thereafter, and instantaneous G:F decreased quadratically as live weight increased for both genders. In addition, backfat depth increased linearly and *Longissimus* muscle area increased quadratically as live weight increased. A second study was carried out with 7 different harvest live weights for individual pigs within pens ranging from 113 to 181 kg to determine the effects of increasing harvest weight on overall growth performance and carcass characteristics. The results of this study suggested that pigs could be reared to heavier harvest weights with relatively limited impact on overall growth performance or carcass leanness. A third study was carried out to evaluate the growth of individual pigs within a pen. Barrows and gilts were housed in single-gender pens of approximately 153 pigs from weaning to week 10 post-weaning and pens with approximately 73 pigs from week 10 post-weaning to a pen mean live weight of 135.2 ± 0.76 kg. Pigs were weighed individually at birth and every 2 weeks from weaning to the end of test. The results of this study suggested that both gender and birth weight impacted the growth curves of individual pigs, that the within-pen standard deviation in live weight increased quadratically with increases in live weight, and that interim weights were relatively poor predictors of subsequent growth of individual pigs within a pen. The final study consisted of a series of analyses which were carried out to determine the most appropriate method of describing the relationships between days on test and live weight and between live weight and various growth performance measures, including ADG, ADFI, G:F, and within-pen variation in live weight. The results of the final study suggest that the relationship between days on test and live weight can be described accurately by a number of nonlinear equations. However, simple polynomial or logarithmic equations between live weight and periodic measures of growth performance provide just as, if not more, accurate estimates than more complicated nonlinear equations. Mixed models were developed with random effects for individual pigs to predict the live weight of individual pigs within a pen across a range of live weights; however, the predictions of within-pen variation were generally inaccurate and lower than the actual measures and, therefore, alternative methods of analysis should be evaluated. The results of these studies can be used in economic modeling to determine the optimum harvest weight in the US swine industry.

Key words: pigs; growth; heavy weights

ACKNOWLEDGEMENTS

I would like to thank Dr. Mike Ellis for his excellent leadership and guidance throughout my graduate career. I truly appreciate the opportunities that he created for me. I would also like to thank the other members of my committee, Drs. Beau Peterson, Floyd McKeith and Donald Bullock, for the input and support that they provided during my completion of this dissertation.

I would like to thank The Maschhoffs, LLC for the funding and resources that they provided during my graduate career. Specifically, I would like to thank Tina Peterson, Ben Isaacson, and James Brauer for their help with completing the live animal studies presented in this dissertation.

I owe a great deal of gratitude to my fellow graduate students, Alvaro Rojo-Gomez, Omarh Mendoza, Chad Pilcher, Chris Puls, Luis Ochoa, Jose Charal, Marleny Mercedes, Hannah Rothe, Nicholas Grohmann, Leah Gesing, Sarah Hardman, Jorge Estrada, and Katie Weitekamp for their help and friendship.

The explanation of nonlinear growth modeling concepts provided by Dr. Allan Schinckel was greatly appreciated.

Lastly, I would like to thank the Lord for all of his blessings, my parents, Andy and Jeanne Shull, for all their love and support, and most importantly, my wife, Emily Shull, for her love and encouragement and willingness to make sacrifices so that I could pursue higher education.

TABLE OF CONTENTS

CHAPTER 1: LITERATURE REVIEW.

The harvest weight of pigs in the US swine industry has gradually increased over time. The optimal harvest weight is one that maximizes the profitability of the entire production system from producer to consumer. From a producer's perspective, it is critical to understand the effect of increasing harvest weight on the growth performance and carcass characteristics of pigs. One method of describing the relationship between growth performance and harvest weight is through the development of growth curves. Growth curves can be developed for the mean of a population or for individual pigs within the population. Additionally, a number of studies have shown that increases in live weight result in an increase in live weight variation (Schinckel et al., 2003; Strathe et al., 2010). Therefore, when discussing harvest weight, the growth of individual pigs within a population should be considered. The objective of this review is to summarize the published literature pertaining to the: 1) Effects of increasing harvest live weight on growth performance and carcass characteristics, 2) Methodologies used to develop growth curves, and 3) Factors that impact the growth of individual pigs within a population.

HARVEST WEIGHT

Several studies have reported on the effects of harvest weight on growth performance and carcass characteristics; however, only studies that have been conducted in the last 25 years will be discussed throughout this thesis. In addition, a number of studies have been carried out using restricted feeding for all of the pigs on test (Virgili et al., 2003; Lo Fiego et al., 2005; Conte et al., 2011); these studies will not be discussed as restrict feeding of pigs has been shown to impact both the growth performance and carcass characteristics of pigs (Donker et al., 1986) and, in addition, the majority of commercial pigs are given ad libitum access to feed.

Growth Performance. A summary of 10 studies that have evaluated the effect of harvest weight on overall growth performance is presented in Table 1. A number of studies have reported no effect of increasing harvest weight on overall ADG (Cisneros et al., 1996; Leach et al., 1996; Weatherup et al., 1998; Latorre et al., 2003; Kim et al., 2004; Latorre et al., 2008), ADFI (Latorre et al., 2004; Latorre et al., 2008; Peinado et al., 2008), and G:F (Cisneros et al., 1996; Latorre et al., 2008). Conversely, other studies have reported a reduction in overall ADG ranging from 1.7 to 4.4 g for each 1 kg increase in harvest weight (Ellis et al., 1996; Candek-Potokar et al., 1998; Latorre et al., 2004; Peinado et al., 2008), an increase in overall ADFI ranging from 7.9 to 11.1 g for each 1 kg increase in harvest weight (Candek-Potokar et al., 1996; Cisneros et al., 1996; Weatherup et al., 1998; Latorre et al., 2003; Kim et al., 2004), and a reduction in overall G:F of 0.0009 to 0.0024 units for each 1 kg increase in harvest weight (Candek-Potokar et al., 1996; Leach et al., 1996; Weatherup et al., 1998; Latorre et al., 2003; Kim et al., 2004; Latorre et al., 2004; Peinado et al., 2008). This range of responses to increasing harvest weight is due, at least in part, to the differences between studies in live weight at start and at harvest and, also, in the genetic potential of the animals used in the studies. Nevertheless, these studies suggest that growth rate and feed efficiency decrease and feed intake increases as live weight at harvest increases between the range of 80 to 160 kg. However, to accurately estimate the incremental changes in growth performance as live weight at harvest increases, the relationship between instantaneous growth performance and live weight must be determined.

Most of the studies that have evaluated the effect of harvest weight on growth performance have been carried out with small group sizes (Table 1). As a result, the change in within-pen variation in live weight with increasing harvest weight has not been widely evaluated.

Studies have shown an increase in the variation in growth within a population of pigs reared in research settings as live weight increased (Andersen and Pedersen, 1996; Schinckel et al., 2003; Strathe et al., 2010). Nevertheless, additional research on the impact of increasing harvest weight on within-pen variation in live weight for pigs reared in commercial facilities is needed.

Carcass Characteristics. A summary of 14 studies that evaluated the effect of harvest weight on carcass characteristics is presented in Table 2. Some studies have reported no effect of increasing harvest weight on carcass yield (Leach et al., 1996; Latorre et al., 2003; Peinado et al., 2008); however, the majority of the studies have reported an increase in carcass yield as harvest weight increased (Table 2). Wagner et al. (1999) evaluated harvest weights ranging from 25 to 152 kg and reported a quadratic increase in carcass yield as harvest weight increased. Conversely, a number of other studies have reported a linear increase in carcass yield as harvest weight increased (Cisneros et al., 1996; Latorre et al., 2004; Latorre et al., 2008). Assuming a linear relationship, improvements in carcass yield across a number of studies ranged from 0.03 to 0.11 percentage units per 1 kg increase in harvest weight (Cisneros et al., 1996; Ellis et al., 1996; Candek-Potokar et al., 1998; Weatherup et al., 1998; Latorre et al., 2004; Correa et al., 2006; Latorre et al., 2008). These results agree with those of Gu et al. (1992) that the rate of growth of the carcass was relatively greater than that of the live animal between harvest weights of 59 and 127 kg. According to Whittemore and Fawcett (1974) and Whittemore (1993), carcass yield increased with body weight (BW) and backfat depth (BF) according to the following equation:

$$\text{Carcass yield} = 66.0 + 0.09*\text{BW (kg)} + 0.12*\text{BF (mm)}.$$

Other factors, such as the visceral organ mass and harvesting method, are likely to have an impact on the relationship between harvest weight and carcass yield.

Nearly all studies reported an increase in backfat depth as harvest weight increased (Table 2). A number of studies reported a linear increase in backfat depth as harvest weight increased (Cisneros et al., 1996; Wagner et al., 1999; Latorre et al., 2004). Assuming a linear relationship, increases in backfat depth between the 10^{th} and last ribs as harvest weight increased ranged between 0.08 and 0.26 mm per 1 kg increase in harvest weight at the 10^{th} rib (Geri et al., 1990; Gu et al., 1992; Cisneros et al., 1996; Ellis et al., 1996; Leach et al., 1996; Weatherup et al., et al., 1998; Wagner et al., 1999; Latorre et al., 2004; Latorre et al., 2008). Two studies showed no effect of harvest weight on backfat depth, however, these did report numerically higher backfat depth for the heavier harvest weight treatments (Latorre et al., 2003; Peinado et al., 2008). Furthermore, those 2 studies evaluated a relatively narrow range of harvest weights (Table 2) and, consequently, it is not unexpected that changes in backfat depth were relatively limited.

Of the 7 studies that measured *Longissimus* muscle area, 6 reported an increase as harvest weight increased and 1 reported no effect of harvest weight (Table 2). Wagner et al. (1999) reported a quadratic increase in *Longissimus* muscle area with increasing harvest weight from 25 to 152 kg. Conversely, Cisneros et al. (1996) reported a linear increase in *Longissimus* muscle area of 0.18 cm^2 for each 1 kg increase in harvest weight from 100 to 160 kg. The difference in the range of harvest weights tested in these 2 studies is the most likely reason for the difference in the relationship between harvest weight and *Longissimus* muscle area. In two studies that compared only 2 harvest weight treatments, Candek-Potokar et al. (1998) reported *Longissimus* muscle areas of 34.7 and 44.1 cm^2 for pigs at harvest weights of 100 and 130 kg, respectively, and Geri et al. (1990) reported areas of 48.4 and 68.1 cm^2 for pigs harvested at 95 and 145 kg live weight, respectively. *Longissimus* muscle depth was only measured in 2 studies (Table 2).

Ellis et al. (1996) reported an increase in *Longissimus* muscle depth as harvest weight increased from 80 to 120 kg, however, Leach et al. (1996) reported similar *Longissimus* muscle depth for harvest weights of 110, 125, and 140 kg. Predicted carcass lean content (%) was reported in only 2 of the 14 studies reviewed and both reported a reduction in predicted carcass lean content as harvest weight increased (Table 2). Specifically, Leach et al. (1996) reported a reduction in predicted carcass lean content of 0.16 percentage units per 1 kg increase in harvest weight from 110 to 140 kg. Obviously, the growth of lean muscle mass of pigs will eventually approach zero as the animal reaches maturity. Therefore, the relationship between harvest weight and *Longissimus* muscle area and depth, as well as, predicted carcass lean content, will be impacted by the maturity rate of pigs used in the studies.

GROWTH CURVES

The ability to predict the weight of pigs throughout all phases of production provides many economic advantages to commercial swine producers. As a result, a number of empirical growth equations have been used to describe the relationship between the live weight and age of pigs. A summary of commonly used equations is presented in Table 3. Plotting the live weight of pigs from birth to maturity against age will result a sigmoidal-shaped curve in which the rate of growth increases to a maximum at the inflection point and then decreases to zero as the animals reach mature body weight. Therefore, these equations typically contain several parameters in order to accurately describe the changes in live weight as pigs increase in age. Wellock et al. (2004) evaluated several equations for the use in predicting growth in an unlimited environment and suggested that the most desirable equation is one that has a limited number of parameters which have biological meaning and result in continuous growth, a single point of inflection, and an asymptote (i.e., zero growth) at maturity. Based on these criteria, the Gompertz equation was recommended.

A number of other studies have evaluated the accuracy of various equations at predicting live weight at a given age. These equations (Table 3) differ in the number of parameters and functional form (e.g., the inflection point is fixed in some equations and is variable in others). Strathe et al. (2010) fitted the Gompertz, Logistic, Bridges, and generalized Michealis-Menten (GMM) equations to live weight data from birth to maturity for barrows, boars, and gilts and concluded that the GMM equation provided the best fit. The pigs (n = 40) used in that study were housed in individual crates with the objective of providing unlimited conditions. Kebreab et al. (2007) compared the Gompertz, Richards, and von Bertalanffy equations and reported that the Richards equation gave the best fit to the data from 48 pigs reared from birth to maturity. Schinckel et al. (2008) evaluated the ability of the Bridges, GMM, and 2^{nd} order polynomial (i.e., quadratic) equations to predict live weight at a given age for pigs reared from 20 to 125 kg live weight. In that study, the lack of data from 125 kg to maturity resulted in extreme estimates of mature BW and a poor fit of the data for the Bridges and GMM equations and, as a result, the quadratic equation was used. This suggests that the live weight range being modeled has a significant impact on which equation provides the best fit to the data. This is a concern because the range in live weights commonly used in empirical growth models is often well below the live weight at maturity. Additionally, nearly all of these studies have been carried out using individual pig data from a relatively limited number of pigs. In commercial research, however, the experimental unit is often a pen of pigs. Therefore, future research should focus on the development of growth curves using pen mean data.

Once an appropriate growth equation has been selected and fitted to the data, the instantaneous growth rate at any age can be calculated by taking the first-order derivative of that equation with respect to age (i.e., d_w/d_t, where d represents the derivative, w is the live weight, and t is the age). Furthermore, the growth of chemical components (e.g., protein and lipid) within the body has also been modeled in a number of studies (Schinckel and de Lange, 1996; Hamilton et al., 2003; Schinckel et al., 2008). The relationships between live weight and protein, lipid, moisture, and ash have been developed using the following equation:

$$Y = a*BW^b,$$

where Y is the variable of interest, BW is the live weight, and a and b are constants) and also using various other equations (Hamilton et al., 2003; Schinckel et al., 2008). Daily accretion rates of chemical components can then be calculated by multiplying the derivative of the specific equation to that of the live weight growth equation as follows:

Daily accretion rate (i.e., d_c/d_t) = $(d_c/d_w)*(d_w/d_t)$,

where d represents the derivative, c is the chemical component mass, w is the live weight, and t is age (Schinckel and de Lange, 1996).

Feed intake in pigs has also been modeled in a number of studies, primarily as a means to estimate the nutrient requirements for growth. However, empirical feed intake prediction models based on live weight (or age) have been proven to be inaccurate (Whittemore et al., 2001). Nevertheless, empirical modeling is valuable for describing the relationships between live weight and feed intake for a particular group of pigs.

A variety of equations have been used to describe the relationship between live weight and instantaneous ADFI. The equation:

$$Y=a*BW^b,$$

where Y is instantaneous ADFI, BW is live weight, and a and b are constants, has been used in a number of studies (Whittemore et al., 1983; Urquhart, 1995). NRC (1998) reported the following polynomial equation for predicting the instantaneous energy intake of pigs as live weight increased:

$$\text{Instantaneous energy intake (MJ digestible energy)} = 5.23 + 0.79*(\text{live weight}) - 0.0059*(\text{live weight})^2 + 0.000018*(\text{live weight})^3.$$

Similarly, Quiniou et al. (2000) described the instantaneous feed intake of pigs as follows:

$$\text{Instantaneous ADFI} = 0.055*(\text{live weight})-0.00025*(\text{live weight})^2.$$

Schinckel et al. (2009) evaluated a number of equations between ADFI and both age and live weight including the 2^{nd} order polynomial, exponential, GMM, and Bridges equations, and concluded that the Bridges equation provided the most appropriate fit to the feed intake data. Anderson and Pedersen (1996) took an alternative approach to modeling feed intake and developed a regression equation between days on test and cumulative feed intake. The first-order derivative of that equation with respect to age on test resulted in an equation for instantaneous ADFI. Few studies have attempted to model the relationship between live weight and feed efficiency. Schinckel et al. (2009) predicted G:F for various live weights by dividing predictions of ADG by predictions of ADFI. Nevertheless, additional research needs to be conducted to determine the most appropriate method of predicting G:F.

Up to this point in this thesis, the focus of the discussion has been on the growth of the mean of an entire population of pigs. In practice, pigs are marketed on an individual basis. Therefore, it is important to understand the variation in growth between individual pigs within a population. A number of studies have developed stochastic growth models to estimate the between pig variation in growth (Craig and Schinckel, 2001; Schinckel et al., 2003; Strathe et al., 2010). Craig and Schinckel (2001) added a random variable to the Bridges equation as follows:

$$BW_{i,t} = W_0+(W_m+w_i)*(1-\exp(-\exp(m)*t^a)) + e_{i,t},$$

where BW is the live weight of the i^{th} pig at age t, W_0 is the initial live weight, W_m is the predicted mature live weight, w_i is the random effect for the i^{th} pig, t is the age of the pig, m and a are constants that determine the shape of the curve to allow the mature BW of pigs to vary, and $e_{i,t}$ is the model error term. More recently, Schinckel et al. (2008) added an additional random variable to adjust both the mature BW and the shape of the curve up to the mature BW for each individual pig. Random variables can also be added for other information collected on each individual pig, such as the random effect of litter and individual pig nested within litter (Strathe et al., 2010). The variance associated with the random variables provides an estimate of the amount of variation within the group or population. In order for stochastic models to be developed for cumulative feed intake, individual pig intake data must be recorded. These data are not easily collected in a commercial production setting with pigs housed in groups. Additional research is required in order to model the growth and feed intake of individual pigs within a pen of pigs in a commercial facility.

INDIVIDUAL PIG GROWTH

The mean growth performance of a group of pigs is comprised of individual pigs that have differing performance levels. This variation around the group mean is an issue because pigs are commonly sold on an individual basis and there are significant price discounts for pigs harvested at weights above and below the desired weight range set by the packer. In addition, opportunities may exist for slower and faster growing pigs to be managed differently in order to improve the performance of the entire population of pigs. Therefore, a significant amount of research has been carried out to determine the factors that impact the growth of individual pigs within a group.

Birth Weight. A number of studies have evaluated the effects of birth weight on pre- and post-weaning growth and have reported that heavy birth weight piglets were heavier at weaning (Milligan et al., 2002; Quiniou et al., 2002; Wolter et al., 2002; Beauleiu et al., 2010; Bérard et al., 2010) and grew faster from weaning to harvest (Wolter et al., 2002; Gondret et al., 2005; Rehfeldt and Kuhn, 2006; Bérard et al., 2008; Peterson, 2008; Puls, 2009; Beauleiu et al., 2010) compared to light birth weight piglets. Schinckel et al. (2007) suggested that predicted live weight at 168 days of age increased cubically as birth weight increased suggesting that, compared to pigs in the middle of the birth weight distribution, heavy birth weight pigs have higher post-weaning growth and light birth weight pigs have lower post-weaning growth. The reduction in pre- and post-weaning growth rate for light birth weight pigs can, at least in part, be attributed to the amount of nutrients transferred from the sow to the fetus (Pond, 1973).

The nutrition of the sow during gestation has been shown to impact birth weight and post-weaning growth performance of pigs. For example, feeding a protein restricted diet to sows during the gestation period has been shown to reduce birth weight and subsequent growth performance (Pond, 1973; Atinmo et al., 1974). It has also been suggested that the lower growth performance in light compared to heavier birth weight pigs is due to a reduction in the number of muscle fibers. The number of primary muscle fibers is determined at birth (Wigmore and Strickland, 1983) and has been shown to be positively correlated with postnatal growth (Dwyer et al., 1993). Light birth weight piglets have been reported to have fewer muscle fibers than heavier birth weight piglets (Hegarty and Allen, 1978; Wigmore and Strickland, 1983; Rehfeldt and Kuhn; 2006). Therefore, it has been suggested that by improving the nutrition of the sow during gestation the muscle fiber number, birth weight, and post-weaning growth performance of the progeny would be increased. Dwyer et al. (1994) reported that feeding 100% above standard requirements for sows during day 25 to 50 of gestation had no impact on primary muscle fiber number but increased the number of secondary muscle fibers and post-weaning growth rates for light birth weight pigs. However, other studies have shown no effect of increasing sow nutrition during gestation on muscle fiber number or post-weaning growth rates (Nissen et al., 2003; Bee, 2004).

Intrauterine crowding has also been suggested to decrease the flow of nutrients to the fetus (Pére and Etienne, 2000) and, consequently, reduce birth weight (Rehfeldt and Kuhn, 2006). Intrauterine crowding is often discussed in conjunction with increases in litter size. A number of studies have reported a reduction in mean piglet birth weight as litter size increased (Milligan et al., 2002; Quiniou et al., 2002; Bérard et al., 2008; Beaulieu et al., 2010). Foxcroft (2006) suggested that reduced mean piglet birth weight due to increased litter size was a result of intrauterine crowding and reduced pre-natal growth of the lightest fetuses. In support of this concept, Bérard et al. (2008) reported an interaction between birth weight category and litter size. In that study, there was no effect of litter size on the birth weight of the heaviest pig within a litter, however, the lightest birth weight pig and pig closest in weight to the mean birth weight of the litter had a lower birth weight, on average, in the large litters (>14 piglets) than in the small litters (<10 piglets). In addition, litter size has been shown in some studies to have no impact on post-natal growth performance (Bérard et al., 2008; Beaulieu et al., 2010). These findings are surprising because pigs from large litters were lighter at birth and light birth weight pigs have been shown to have reduced post-natal growth. Thus, further research is required to understand the interaction between litter size and individual pig birth weight within a liter in terms of post-natal growth.

Weaning Weight. Heavier pigs at weaning have been shown in a number of studies to have higher post-weaning growth rates than their lighter-weight counterparts (Cabrera et al., 2002; Klindt, 2003; Schinckel et al., 2007). However, in these studies, the pigs that were heavier at weaning were also heavier at birth, which has been shown to impact post-natal growth (Peterson, 2008; Puls, 2009). More recently, studies have been designed to evaluate the effect of weaning weight separately from the effect of birth weight. Wattanakul et al. (2007) compared pigs with reduced weaning weights, due to a restriction in the amount of time the piglets were given with the sow, to pigs with heavier weaning weights that had full access to the sow at all times and reported that pigs with reduced weaning weight grew faster during the first 28 days post-weaning and similar over the entire test period. Peterson (2008) created a heavy and light weaning weight treatment by rearing piglets to weaning in litters of either 6 or 12 pigs, respectively, and reported no effect of weaning weight treatment on post-weaning growth. Furthermore, a number of studies that have increased weaning weights by providing supplemental nutrition to the piglets have reported that any advantage in live weight at weaning was lost in subsequent growth periods (Wolter et al., 2002; Klindt, 2003). These results suggest that, independent of any effect of birth weight, weaning weight per se has little impact on post-weaning growth rate.

Other Factors. A number of other factors, such as floor space, have been shown to impact the growth of pigs in a commercial production system. However, floor space, for example, has been shown to have no impact on the within-pen variability in live weight (Shull, 2010). This suggests that each pig within the pen is impacted by reduced floor space to a similar degree and provides little explanation of the variability in growth rates between pigs. Social dominance of pigs within a pen has been shown to have a positive correlation with post-weaning growth (Beilharz and Cox, 1967; Giroux et al., 2000). However, in those studies, the heavier pigs were typically more dominant than lighter pigs. Therefore, it is difficult to separate the effects of social dominance from the effects of birth weight and/or weaning weight. Pomar et al. (2003) proposed that some of the variation in growth rate of pigs within a pen could be attributed to the fact that the same diet is given to every pig. Diets are commonly formulated to meet the requirements of a pig at a live weight near the mean of the population. As a result, the diets are formulated to be above the nutrient requirements of heaviest pigs and below those of the lightest pigs. This, however, becomes more complicated with differing levels of feed intake and lean growth rate between the heaviest and lightest pigs in the pen. Other factors, such as health status, are likely to influence the growth of individual pigs within a pen; however, there has been little or no research carried out to investigate the effect of disease on variation in growth within a population of pigs.

LITERATURE CITED

Andersen, S. and B. Pedersen. 1996. Growth and food intake curves for group-housed gilts and castrated male pigs. Anim. Sci. 63:457-464.

Atinmo, T., W. G. Pond, and R. H. Barnes. 1974. Effect of maternal energy vs. protein restriction on growth and development of progeny in swine. J. Anim. Sci. 39:703-711.

Bee, G. 2004. Effect of early gestation feeding, birth weight, and gender of progeny on muscle fiber characteristics of pigs at slaughter. J. Anim. Sci. 82:826-836.

Beilharz, R. G. and D. F. Cox. 1967. Social dominance in swine. Anim. Behav. 15:117-122.

Bérard, J., M. Kreuzer, and G. Bee. 2008. Effect of litter size and birth weight on growth, carcass and pork quality, and their relationship to postmortem proteolysis. J. Anim. Sci. 86:2357-2368.

Bérard, J., M. Kreuzer, and G. Bee. 2010. In large litters birth weight and gender is decisive for growth performance but less for carcass and pork quality traits. Meat Sci. 86:845-851.

Beauleiu, A. D., J. L. Aalhus, N. H, Williams, and J. F. Patience. 2010. Impact of piglet birth weight, birth order, and litter size on subsequent growth performance, carcass quality, muscle composition, and eating quality of pork. J. Anim. Sci. 88:2767-2778.

Bertalanffy, L. von. 1957. Quantitative laws for metabolism and growth. Quart. Rev. Biol. 32:217-232.

Bridges, T. C., U. W. Turner, E. M. Smith, T. S. Stahly, and O. J. Loewer. 1986. A mathematical procedure for estimating animal growth and body composition. Trans. ASAE. 29:1342-1347.

Cabrera, R., S. Jungst, R. D. Boyd, M. E. Johnson, E. Wilson, and J. L. Usry. 2002. Impact of pig weight at weaning. II. post-weaning growth and economic assessment of weights ranging from 4.1 to 8.6 kg. J. Anim. Sci. 80(Suppl. 1):199. (Abstr.)

Čandek-Potokar, M., B. Žlender, L. Lefaucheur, and M. Bonneau. 1998. Effects of age and/or weight at slaughter on *longissimus dorsi* muscle: Biochemical traits and sensory quality in pigs. Meat Sci. 48:287-300.

Cisneros F., M. Ellis, F. K. McKeith, J. McCaw, and R. L. Fernando. 1996. Influence of slaughter weight on growth and carcass characteristic, commercial cutting and curing yields, and meat quality of barrows and gilts from two genotypes. J. Anim. Sci. 74:925-933.

Conte, S., L. A. Boyle, N. E. O'Connell, P. B. Lynch, and P. G. Lawlor. 2011. Effect of target slaughter weight on production efficiency, carcass traits and behavior of restrictively-fed gilts and intact male finisher pigs. Livest. Sci. 136:169-174.

Correa, J. J., L. Faucitano, J. P. Laforest, J. Rivest, M. Marcoux, and C. Gariépy. 2006. Effects of slaughter weight on carcass composition and meat quality in pigs of two different growth rates. Meat Sci. 72:91-99.

Correa, J. A., C. Gariepy, M. Marcoux, L. Faucitano. 2008. Effects of growth rate, sex, and slaughter weight on fat characteristics of pork bellies. Meat Sci. 80:550-554.

Craig, B. A. and A. P. Schinckel. 2001. Nonlinear mixed effects model for swine growth. Prof. Anim. Sci. 17:256-260.

Donker, R. A., L. A. Den Hartog, E. W. Brascamp, J. W. M. Merks, G. J. Noordewier, and G. A. J. Buiting. 1986. Restriction of feed intake to optimize the overall performance and composition of pigs. Livest. Prod. Sci. 15:353-365.

Dwyer, C. M., J. M. Fletcher, and N. C. Stickland. 1993. Muscle cellularity and postnatal growth in the pig. J. Anim. Sci. 71:3339-3343.

Dwyer, C. M., N. C. Stickland, and J. M. Fletcher. 1994. The influence of maternal nutrition on muscle fiber number development in the porcine fetus and on subsequent postnatal growth. J. Anim. Sci. 72:911-917.

Ellis, M., A. J. Webb, P. J. Avery, and I. Brown. 1996. The influence of terminal sire genotype, sex, slaughter weight, feeding regime and slaughter-house on growth performance and carcass and meat quality in pigs and on the organoleptic properties of fresh pork. Anim. Sci. 62:521-530.

Foxcroft, G. R., W. T. Dixon, S. Novak, C. T. Putman, S. C. Town and M. D. A. Vinsky. 2006. The biological basis for prenatal programming of postnatal performance in pigs. J. Anim. Sci. 84(E. Suppl.):E105-E112.

Geri, G., O. Franci, B. M. Poli, G. Campodoni, and A. Zappa. 1990. Relationships between adipose tissue characteristics of newborn pigs and subsequent performance: II. Carcass traits at 95 and 145 kilograms live weight. J. Anim. Sci. 68:1929-1935.

Giroux, S., G. P. Martineau, S. Robert. 2000. Relationships between individual behavioural traits and post-weaning growth in segregated early-weaned piglets. Appl. Anim. Behav. Sci. 70:41-48.

Gompertz, B. 1825. On nature of the equation expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Phil. Trans. Roy. Soc. 115:513-585.

Gondret, F., L. Lefaucheur, I. Louveau, B. Lebret, X. Pichodo, and Y. Le Cozier. 2005. Influence of piglet birth weight on postnatal growth performance, tissue lipogenic capacity and muscle histological traits at market weight. Livest. Prod. Sci. 93:137-146.

Gu, Y., A. P. Schinckel, and T. G. Martin. 1992. Growth, development, and carcass composition in five genotypes of swine. J. Anim. Sci. 70:1719-1729.

Hamilton, D. N., M. Ellis, B. F. Wolter, A. P. Schinckel, and E. R. Wilson. 2003. The growth performance of the progeny of two swine sire lines reared under different floor space allowances. J. Anim. Sci. 81:1126-1135.

Hegarty, P. V. J. and C. E. Allen. 1978. Effect of pre-natal runting on the post-natal development of skeletal muscles in swine and rats. J. Anim. Sci. 46:1634-1640.

Kebreab, E., M. Schulin-Zeuthen, S. Lopez, J. Soler, R. S. Dias, C. F. M. de Lange, and J. France. 2007. Comparative evaluation of mathematical equations to describe growth and efficiency of phosphorous utilization in growing pigs. J. Anim. Sci. 85:2498-2507.

Kim, Y. Y., J. R. Piao, J. Z. Tian, B. G. Kim, Y. I. Choi, and In. K. Han. 2004. Effects of sex and market weight on performance, carcass characteristics and pork quality of market hogs. Asian-Aust. J. Anim. Sci. 17:1452-1458.

Klindt, J. 2003. Influence of litter size and creep feeding on pre-weaning gain and influence of pre-weaning growth on growth to slaughter in barrows. J. Anim. Sci. 83:2434-2439.

Latorre, M. A., E. Garcia-Belenguer, and L. Arino. 2008. The effects of sex and slaughter weight on growth performance and carcass traits of pigs intended for dry-cured ham from Teruel (Spain). J. Anim. Sci. 86:1933-1942.

Latorre, M. A., P. Medel, A. Fuentetaja, R. Lázaro, and G. G. Mateos. 2003. Effect of gender, terminal sire line and age at slaughter on performance, carcass characteristics and meat quality of heavy pigs. Anim. Sci. 77:33-45.

Latorre, M. A., R. Lazaro, D. G. Valencia, P. Medel, and G. G. Mateos. 2004. The effects of gender and slaughter weight on the growth performance, carcass traits, and meat quality characteristics of heavy pigs. J. Anim. Sci. 82:526-533.

Leach, L. M., M. Ellis, D. S. Sutton, F. K. McKeith, and E. R. Wilson. 1996. The growth performance, carcass characteristics, and meat quality of halothane carrier and negative pigs. J. Anim. Sci. 74:934-943.

Lopez, S., J. France, W. J. Gerrits, M. S. Dhanoa, D. J. Humphries, and J. Dijkstra. 2000. A generalized Michaelis-Menten equation for the analysis of growth. J. Anim. Sci. 78:1816-1828.

Lo Fiego, D. P., P. Santoro, P. Macchioni, and E. De Leonibus. 2005. Influence of genetic type, live weight at slaughter and carcass fatness on fatty acid composition of subcutaneous adipose tissue of raw ham in the heavy pig. Meat Sci. 69:107-114.

Milligan, B. N., D. Fraser, and D. L. Kramer. 2002. Within-litter birth weight variation in the domestic pig and its relation to pre-weaning survival, weight gain, and variation in weaning weights. Livest. Prod. Sci. 76:181-191.

NRC. 1998. Nutrient Requirements of Swine (10th Ed.). National Academy Press. Washington, DC.

Nissen, P. M., V. O. Danielson, P. F. Jorgensen, and N. Oksbjerg. 2003. Increased maternal nutrition of sows has no beneficial effects on muscle fiber number or postnatal growth and has no impact on meat quality of the offspring. J. Anim. Sci. 81:3018-3027.

Peinado, J., P. Medel, A. Fuentetaja, and G. G. Mateos. 2008. Influence of sex and castration of females on growth performance and carcass and meat quality of heavy pigs destined for the dry-cured industry. J. Anim. Sci. 86:1410-1417.

Pére, M. C. and M. Etienne. 2000. Uterine blood flow in sows: effects of pregnancy stage and litter size. Reprod. Nutr. Dev. 40:369-382.

Peterson, B. A. 2008. Effects of birth weight on growth performance, tissue accretion, and carcass composition of barrows to 145 kg body weight. PhD Diss. University of Illinois, Urbana.

Pomar, C., I. Kyriazakis, G. C. Emmans, and P. W. Knap. 2003. Modeling stochasticity: Dealing with populations rather than individual pigs. J. Anim. Sci. 81(E. Suppl. 2):E178-E186.

Pond, W. G. 1973. Influence of maternal protein and energy nutrition during gestation on progeny performance in swine. J. Anim. Sci. 36:175-182.

Puls, C. L. 2009. Effects of birth weight and paylean inclusion level on the growth performance, carcass characteristics, and fresh pork quality parameters of pigs. MS Thesis. University of Illinois, Urbana.

Quiniou, N., J. Dagorn, and D. Gaudre. 2002. Variation in piglets' birth weight and consequences on subsequent performance. Livest. Prod. Sci. 78:63-70.

Quiniou, N., S. Dubois, and J. Noblet. 2000. Voluntary feed intake and feeding behavior of group housed pigs are effected by ambient temperature and body weight. Livest. Prod. Sci. 63:245-253.

Rehfeldt, C, and G. Kuhn. 2006. Consequences of birth weight for postnatal growth performance and carcass quality in pigs as related to myogenesis. J. Anim. Sci. 84(E. Suppl.):E113-E123.

Richards, F. J. 1959. A flexible growth equation for empirical use. J. Exp. Bot. 10:290-300.

Robertson, T. B. 1908. On the normal growth rate of an individual and its biochemical significance. Archiv f ür Entwicklungsmechanik der Organismen 25:581-614.

Schinckel, A. P. and C. F. de Lange. 1996. Characterization of growth parameters needed as inputs for pig growth models. J. Anim. Sci. 74:2021-2036.

Schinckel, A. P., D. C. Mahan, T. G. Wiseman, and M. E. Einstein. 2008. Growth of protein, moisture, lipid, and ash of two genetic lines of barrows and gilts from twenty to one hundred twenty-five kilograms of body weight. J. Anim. Sci. 86:460-471.

Schinckel, A. P., N. Li, P. V. Preckel, M. E. Einstein, and D. Miller. 2003. Development of a stochastic pig compositional growth model. Prof. Anim. Sci. 19:255-260.

Schinckel, A. P., M. E. Einstein, S. Jungst, C. Booher, and S. Newman. 2009. Evaluation of different mixed model nonlinear functions to describe the feed intakes of pigs of different sire and dam lines. Prof. Anim. Sci. 25:345-359.

Schinckel, A. P., R. Cabrera, R. D. Boyd, S. Jungst, C. Booher, M. Johnston, and M. E. Einstein. 2007. Impact of birth and body weight at twenty days on the postweaning growth of pigs with different weaning management. Prof. Anim. Sci. 23:197-210.

Shull, C. M. 2010. Effect of floor space in the nursery and grow-finish periods on the growth performance of pigs. MS Thesis. University of Illinois, Urbana.

Strathe, A. B., A. Danfaer, H. Sorensen, and E. Kebreab. 2010. A multilevel nonlinear mixed-effects approach to model growth in pigs. J. Anim. Sci. 88:638-649.

Urquhart, R. 1995. Studies on the regulation of energy intake and body composition of growing pigs. PhD Diss. The Queen's University, Belfast.

Virgili, R., M. Degni, C. Schivazappa, V. Faeti, E. Poletti, G. Marchetto, M. T. Pacchioli, and A. Mordenti. 2003. Effect of age at slaughter on carcass traits and meat quality of Italian heavy pigs. J. Anim. Sci. 81:2448-2456.

Wagner, J. R., A. P. Schinckel, W. Chen, J. C. Forrest, and B. L. Coe. 1999. Analysis of body composition changes of swine during growth and development. J. Anim. Sci. 77:1442-1466.

Wattanakul, W., J. A. Rooke, A. H. Stewart, P. R. English, and S. A. Edwards. 2007. Effect of milk deprivation during the lactation period on performance and digestive enzyme activities of the piglets following weaning. Animal. 1:381-387.

Weatherup, R. N., V. E. Beattie, B. W. Moss, D. J. Kilpatrick, and N. Walker. 1998. The effect of increasing slaughter weight on the production performance and meat quality of finishing pigs. Anim. Sci. 67:591-600.

Wellock, I. J., G. C. Emmans, and I. Kyriazakis. 2004. Describing and predicting potential growth in the pig. Anim. Sci. 78:379-388.

Whittemore, C. T. 1983. Development of recommended energy and protein allowances for growing pigs. Agric. Syst. 11:156-186.

Whittemore, C. T. 1993. The Science and Practice of Pig Production. Longman Group UK, Essex, England.

Whittemore, C. T., D. M. Green, and P. W. Knap. 2001. Technical review of the energy and protein requirements of growing pigs: food intake. Anim. Sci. 73:3-17.

Whittemore, C. T. and R. Fawcett. 1974. Theoretical aspects of a flexible model to simulate lipid and protein growth in pigs. Anim. Prod. 22:87-96.

Wigmore, P. M. C. and N. C. Stickland. 1983. Muscle development in large and small pig fetuses. J. Anat. 137:235-245.

Wolter, B. F., M. Ellis, B. P. Corrigan, and J. M. DeDecker. 2002. The effect of birth weight and feeding of supplemental milk replacer to piglets during lactation on pre-weaning and post-weaning growth performance and carcass characteristics. J. Anim. Sci. 80:301-308.

TABLES

Table 1. Summary of literature for effects of harvest weight on overall growth performance.[1]

Study	Harvest weight treatments	Initial BW, kg	Floor space, m^2/pig	Group size	Exp. units /treatment	Total # of pigs	Gender[3]	Relationship with HW[2] ADG	ADFI	G:F
Candek-Potokar et al. (1998)[4]	100, 130	32	NA	NA	NA	40	CM	−	+	−
Cisneros et al. (1996)	100, 115, 130, 145, 160	60	1.2	4	8	160	CM, IF	NS	+	NS
Ellis et al. (1996)	80, 100, 120	35	NA	10	30	897	CM, IF	−	NA	NA
Kim et al. (2004)	100, 110, 120, 130	27	NA	NA	NA	224	CM, IF	NS	+	−
Latorre et al. (2003)	122, 136	25	1.1	5	24	240	CM, IF	NS	+	−
Latorre et al. (2004)	116, 124, 133	75	1.0	8	8	192	CM, IF	−	NS	−
Latorre et al. (2008)	120, 125, 130, 135, 140	107	1.1	10	4	200	CM, IF	NS	NS	NS
Leach et al. (1996)	110, 125, 140	43	1.2	4	12	144	CM, IF	NS	NA	−
Peinado et al. (2008)	114, 122	61	0.8	10	10	240	CM, IF, CF	−	NS	−
Weatherup et al. (1998) exp 1	92, 103, 114, 125	50	6.0	1	16	96	IM, CM, IF	NS	+	−

[1]"NA" = not available.
[2]"NS" = no effect ($P > 0.05$) of harvest weight; "+" = increased as harvest weight increased; "−" = decreased as harvest weight increased.
[3]"IM" = intact male; "CM" = castrated male; "IF" = intact female; "CF" = castrated female.
[4]Excludes data from restrict-fed pigs.

Table 2. Summary of literature for effects of harvest weight on carcass characteristics.[1]

Study	Harvest weight treatments	Initial BW, kg	Floor space, m^2/pig	Group size	Exp. units /treatment	Total # of pigs	Gender[3]	Relationship with HW[2]				
								Yield	BF	LMA	LMD	FFL,%
Candek-Potokar et al. (1998)[4]	100, 130	32	NA	NA	NA	40	CM	+	+	+	NA	NA
Cisneros et al. (1996)	100, 115, 130, 145, 160	60	1.2	4	8	160	CM, IF	+	+	+	NA	NA
Correa et al. (2006)	107, 115, 125	NA	NA	NA	NA	119	CM, IF	+	NA	NA	NA	NA
Correa et al. (2008)	107, 115, 125	NA	NA	NA	NA	119	CM, IF	NA	+	NA	NA	NA
Ellis et al. (1996)	80, 100, 120	35	NA	10	30	897	CM, IF	+	+	+	+	NA
Geri et al. (1990)	95, 145	NA	NA	NA	NA	253	CM, IF	NA	+	+	NA	NA
Gu et al. (1992)	59, 100, 114, 127	NA	NA	1	32	127	CM	NA	+	+	NA	NA
Latorre et al. (2003)	122, 136	25	1.1	5	24	240	CM, IF	NS	NS	NA	NA	NA
Latorre et al. (2004)	116, 124, 133	75	1.0	8	8	192	CM, IF	+	+	NA	NA	NA
Latorre et al. (2008)	120, 125, 130, 135, 140	107	1.1	10	4	200	CM, IF	+	+	NA	NA	NA
Leach et al. (1996)	110, 125, 140	43	1.2	4	12	119	CM, IF	NS	+	NS	NS	−
Peinado et al. (2008)	114, 122	61	0.8	10	10	240	CM, IF, CF	NS	NS	NA	NA	NA
Wagner et al. (1999)	25, 45, 64, 84, 100, 114, 129, 152	NA	NA	NA	NA	319	CM, IF	+	+	+	NA	NA
Weatherup et al. (1998) exp 1	92, 103, 114, 125	50	6.0	1	16	96	IM, CM, IF	+	+	NA	NA	−

[1]"NA" = not available.
[2]"NS" = no effect of harvest weight; "+" = increased as harvest weight increased; "−" = decreased as harvest weight increased.
[3]"IM" = intact male; "CM" = castrated male; "IF" = intact female; "CF" = castrated female.
[4]Excludes data from restrict-fed pigs.

Table 3. A summary of growth equations.

Reference	Name	Equation[1]	Number of parameters
Gompertz (1825)	Gompertz	W_m*exp(-exp(-G-(k-t)))	3
Robertson (1908)	Logistic	W_m/(1+((W_m-W_0)/W_0)*(exp-(W_m*k*t)	3
Bertalanffy (1957)	von Bertalanffy	$\{n/k-(n/k-W_0^{(1-m)})*exp^{-(1-m)k*t}\}^{1/(1-m)}$	4
Richards (1959)	Richards	$W_0*W_m/(W_0^n+(W_m^n-W_0^n)*exp(-k*t)))^{1/n}$	4
Bridges et al. (1986)	Bridges	$W_0+W_m*(1-exp(-exp(m*t^a)))$	4
Lopez et al. (2000)	Generalized Michaelis-Menten (GMM)	$(W_0*k^c+W_m*t^c)/(k^c+t^c)$	4
N/A	Polynomial	$b_0+b_1*t+b_2*t+\ldots+b_n*t$	n

[1]W_0 is the initial live weight, W_m is the live weight at maturity, and t is age. All other parameters (i.e., b, c, G, k, m, and n) are constants that are specific to a particular equation and determine the shape of the curve.

CHAPTER 2: DEVELOPMENT OF GROWTH CURVES FOR PIGS REARED TO HEAVY WEIGHTS.

ABSTRACT

The objective of this research was to develop growth curves of live animal growth performance and ultrasound measures for entire pens of pigs reared to heavy live weights in a commercial wean-to-finish facility. The study was conducted as a RCBD with a single treatment, namely gender (barrows and gilts). The study was carried out using 6 replicates with 240 pigs in 12 pens of 20 from weaning to a pen mean live weight of 167.5 ± 3.30 kg. Pigs had ad libitum access to feed and water throughout the study and were provided a floor space of 1.06 m^2/pig. From start to end of study, barrows grew 3.7% faster ($P \leq 0.05$), consumed 5.4% more feed ($P \leq 0.05$), and tended to have a lower G:F ratio (1.9%; $P = 0.08$) than gilts. Ultrasound measures taken at the end of test showed that gilts had 9.6% less backfat ($P \leq 0.05$), 5.2% larger *Longissimus* muscle area ($P \leq 0.05$), and had numerically greater predicted carcass lean weight (2.5%; $P = 0.13$). Instantaneous ADG peaked at approximately 78 and 77 kg live weight for barrows and gilts, respectively, and decreased thereafter. Instantaneous ADFI peaked at approximately 115 and 121 kg for barrows and gilts, respectively, and decreased subsequently. Instantaneous G:F decreased quadratically as live weight increased for both barrows and gilts. As live weight increased, backfat depth increased linearly and *Longissimus* muscle area increased quadratically for both barrows and gilts, and predicted carcass lean weight increased linearly for barrows and quadratically for gilts. This study provides estimates of the effect on growth and carcass traits of taking contemporary pigs to live weights considerably above current US harvest weight.

INTRODUCTION

One of the key decisions facing swine producers is the optimum weight at which to harvest pigs. Historically, harvest weights have increased over time; however, over the last 10 years, harvest weights in the US have averaged between 120 to 125 kg (USDA-NASS, 2012). Increasing harvest weights can potentially reduce the overhead costs for producers, packers, and processers (Ellis and Bertol, 2001). Other advantages exist for increasing harvest weight, such as increased belly thickness (Correa et al., 2008) and belly curing yields (Cisneros et al., 1996). However, studies have shown that increasing harvest weight results in a reduction in feed efficiency and increased carcass fatness (Kanis et al., 1990; Latorre et al., 2004; Latorre et al., 2008); however, continued genetic improvement in carcass leanness suggests that harvest weights could be increased with minimal impact on carcass leanness and feed efficiency.

In order to determine the economic impact of increasing harvest weights for the producer, the relationships between live weight and the rate and efficiency of growth of the whole body and tissues within the body must be clearly understood. These relationships can be described mathematically using various equations (Schinckel et al., 2006; Strathe et al., 2010). Several studies have been carried to model the growth of pigs; however, most of these studies were carried out in research settings that are not typical of commercial production. Additionally, few studies have developed growth relationships above harvest weights of 125 kg. Therefore, the objective of this research was to develop growth curves of live animal growth performance and ultrasound measures for entire pens of pigs reared in a commercial facility to heavier live weights than typically used in commercial production (i.e., >125 kg).

MATERIALS AND METHODS

The study was conducted in a standard wean-to-finish facility at The Maschhoffs' Georgia Technology Center located near New Minden, IL. The experimental protocol was approved by the University of Illinois Institutional Animal Care and Use Committee (IACUC #10216).

Experimental Design and Treatments. The study was conducted as a randomized complete block design with a single treatment, namely gender (barrows and gilts). Pen was the experimental unit and the location of the pens within a room was the blocking factor.

Animals, Allotment, and Study Period. A total of 240 pigs (6 replicates) were used with 12 pens of 20 animals. Pigs were the progeny of PIC 359 sires mated to PIC C22 or PIC C29 dams (PIC, Hendersonville, KY). Dam line was not taken into account in the allotment of pigs to the study because the litter of origin of the pigs was not known. Immediately following weaning, pigs were weighed individually, tagged, and a barrow and gilt with similar body weight were selected and placed into separate pens. This process was repeated until there were 20 barrows and 20 gilts in each pen. The study was carried out from weaning to a pen mean live weight of 167.5 ± 3.30 kg.

Housing and Diets. Pigs were housed in a wean-to-finish building that had fully slatted concrete flooring and was tunnel ventilated. Pen divisions consisted of gates with horizontal steel rods and pen dimensions (length x width) were 7.16 x 3.05 m, which provided a floor space of 1.06 m^2/pig. This floor space was predicted, based on previous published research, to have no impact on growth performance. However, there have been no studies carried out to determine the relationship between floor space and growth performance of pigs reared to the heavier weights evaluated in this study. In the event of a mortality or removal of a morbid pig during the study, pen size was adjusted using a moveable partition to maintain the correct floor space. Air temperature was maintained using thermostatically controlled heaters and fan ventilation. The thermostat was set at 27° C for the first week and lowered in subsequent weeks until it reached 18° C where it was maintained for the duration of the study. During the first 14 days post-weaning, supplemental heat was provided by one heat reflective heat lamp (125 W) per pen suspended 75 cm above the floor. Under hot conditions when the ambient room temperature reached 29.4° C, water sprinklers were used in an attempt to cool the pigs.

Each pen was equipped with one 5-hole wet/dry box feeder (Feed Ease Wet/Dry Feeder, A. J. O'Mara Group, Lyons, NE) mounted in the fence line. One feeder hole was covered, providing only 4 holes with 142.2 cm of feeder trough space (7.1 cm/pig). An additional cup-type water drinker was provided in each pen. Pigs were provided ad libitum access to feed and water. An 8-phase dietary program was used and diets were formulated to meet or exceed NRC (1998) recommendations for nutrient requirements for pigs across the weight range used. The final dietary phase, which was fed from approximately 115 kg live weight to the end of test, was formulated to the requirement of a 115 kg pig.

Growth Measurements. Pigs were weighed individually at the start and end of test and every 2 weeks from 14 weeks post-weaning to the end of test. Pen weights were collected at the start and end of test and every 2 weeks throughout the study. Feed data were collected using a computerized feed-mixing (L.O.M.A.N. Systmetechovik, Bremerhaven, Germany) and feed delivery (ASA International, Medolago, Italy) system that recorded the weight of feed delivered to each feeder. The amount of feed left in the feeder was also recorded for each pen at the time that the pen weights were collected to calculate feed intake and gain:feed ratio. Pigs experiencing health problems or injuries that did not respond to treatment were removed from the study and the date of, pig weight at, and reason for removal were recorded; the weight of pigs removed was included in the calculation of growth rate and feed efficiency. From week 14 post-weaning to the end of test, an ultrasound scan was taken on each pig at the time of weighing using an Aloka Model 500V B-mode scanner fitted with an Aloka 5011 probe (Corometrics Medical Systems, Wallingford, CT). The image was taken transversely over the tenth rib and backfat depth and *Longissimus* muscle area were manually measured on the image.

Statistical Analysis. All data were tested for normality using the PROC UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC). Morbidity and mortality data were not normally distributed and were analyzed using a Chi-square rank-based test (Steel and Torrie, 1980) using the PROC RANK procedure of SAS. Data meeting the criteria for normality were analyzed using the PROC MIXED procedure of SAS as a randomized complete block design with pen as the experimental unit. The model included the fixed effect of gender and the random effect of block. Least-squares means were compared using the PDIFF and STDERR options of SAS with means considered different with $P \leq 0.05$.

Polynomial regression analysis was conducted separately for each gender using the PROC MIXED procedure of SAS and the model included the random effect of pen. Equations were developed to determine the relationship between the period mean live weight, which was calculated as the mean of the pen mean live weights at the start and end of a 2-week period, and instantaneous ADG, ADFI, and G:F. Equations were also developed to determine the relationship between live weight at the time of weight collection (starting at week 14 post-weaning) and within-pen coefficient of variation in live weight, backfat depth, *Longissimus* muscle area, and predicted carcass lean weight. For all equations, the quadratic and cubic terms were only included in the final model if they were statistically significant ($P \leq 0.05$) using a log-likelihood evaluation. The coefficient of determination (R^2) and residual standard deviation (RSD) were calculated for each regression equation.

RESULTS AND DISCUSSION

Growth performance data are presented in Tables 4 and 5 and live animal ultrasound measures are presented in Table 6. From start to end of study, barrows grew 3.7% faster ($P \leq 0.05$), consumed 5.4% more feed ($P \leq 0.05$), and tended to have a lower G:F ratio (1.9%; $P = 0.08$) than gilts. Ultrasound measures taken at the end of the study showed that gilts had 9.6% less backfat ($P \leq 0.05$), 5.2% larger *Longissimus* muscle area ($P \leq 0.05$), and had numerically greater predicted carcass lean weight (2.5%; $P = 0.13$). These results are similar to those of other studies who have compared barrows and gilts reared to heavier live weights (Cisneros et al., 1996; Wagner et al., 1999; Latorre et al., 2008). Within-pen coefficient of variation in live weight at the end of the study tended ($P = 0.06$) to be higher for gilts than barrows. Additional research with more experimental units is required to validate this finding.

Regression Analysis. The results of the regression analysis are presented in Table 7 and illustrated graphically in Figures 1 to 7.

The linear, quadratic, and cubic terms were significant ($P \leq 0.05$) for the regression of instantaneous ADG against live weight, whereas, only the linear and quadratic terms were significant ($P \leq 0.05$) for ADFI (Table 7). Predicted instantaneous ADG peaked at approximately 78 and 77 kg live weight for barrows and gilts, respectively, and decreased thereafter (Figure 1). These results agree with those of Schinckel et al. (2006) who reported a peak in instantaneous growth rate for barrows and gilts at approximately 83 and 74 kg, respectively. Predicted instantaneous ADFI increased as live weight increased up to approximately 115 and 121 kg for barrows and gilts, respectively, and then decreased, with barrows consuming more feed than gilts over the majority of the weight range evaluated (Figure 2). It is not clear why feed intake declined towards the end of test in the current study. Few studies have reported on the change in instantaneous feed intake at the live weights evaluated in the current study. Latorre et al. (2008) reported numerically similar ADFI for 4 pens of 10 pigs (5 barrows and 5 gilts) between live weight ranges of 107 to 120 kg, 120 to 125 kg, 125 to 130 kg, 130 to 135 kg, and 135 to 140 kg. Many factors can potentially impact the feed intake of pigs (e.g., environmental temperature) and in order to develop a comprehensive model of the growth performance of pigs reared to heavy weights, pigs should, in theory, be evaluated at those weights under a range of conditions that are likely to exist in commercial production.

The results of the regression analysis suggested that instantaneous G:F decreased quadratically as live weight increased for both barrows and gilts (Table 7), with the most rapid decline occurring from weaning to ~25 kg live weight (Figure 3). Above 50 kg live weight, instantaneous G:F was generally higher for gilts than barrows up until approximately 150 kg live weight, at which point barrows and gilts were similar. Several studies carried out to lighter weights (<135 kg) have shown that feed efficiency is greater for gilts compared to barrows (Kanis et al., 1990; Augspurger et al., 2002; Latorre et al., 2004). A possible explanation for the lack of difference between genders in instantaneous G:F above approximately 150 kg could be the onset of estrus in gilts. Amaral Filha et al. (2009) reported that the mean age in which estrus was first observed for gilts was between 160 and 175 days and that exposing gilts to boars can reduce the age at first estrus by 10 days or more. Nevertheless, it is highly probable that most gilts in the current study experienced estrus at least once. Gilts experiencing estrus could have reduced feed intake and possibly lower feed efficiency. The impact of estrus on the growth performance of group-housed gilts is not fully understood and needs further research.

As live weight increased, backfat depth increased linearly (Table 7 and Figure 5) and *Longissimus* muscle area increased quadratically (Table 7 and Figure 6). Specifically, backfat depth at the 10th rib was predicted to increase by 0.18 and 0.17 mm for each 1 kg increase in live weight for barrows and gilts, respectively (Table 7). These results are within the range of several studies, which have reported an increase in backfat depth ranging from 0.16 to 0.25 mm per 1 kg increase in harvest weight with harvest weights ranging from 100 to 160 kg (Cisneros et al., 1996; Leach et al., 1996; Latorre et al., 2004; Latorre et al., 2008). Cisneros et al. (1996) reported a linear increase in *Longissimus* muscle area of 0.18 cm^2 per 1 kg increase in harvest weight from 100 to 160 kg. Leach et al. (1996), however, reported no effect of increasing harvest weight from 110 to 140 kg on *Longissimus* muscle area. Wagner et al. (1999) evaluated harvest weights from 25 to 152 kg and reported very similar results to the current study, with increases in live weight resulting in linear increases in backfat depth and quadratic increases in *Longissimus* muscle area and quadratic increases in fat-free lean weight. In the current study, as live weight increased the total weight of predicted carcass lean increased linearly for barrows and quadratically for gilts (Table 7 and Figure 7) with the predicted carcass lean weight being higher for gilts than barrows across most of the range of weights evaluated. The rates of change in carcass measures of pigs across the range of live weights used in the current study are largely dependent on the genetic potential and maturity patterns of the animals. Nevertheless, the pigs used in the current study demonstrated a continued increase in lean mass (Figure 7) with modest increases in fat depth (Figure 5) as live weight increased.

The coefficient of variation (CV) in live weight within a pen is another important measure with potential economic implications. In the current study, the predicted within-pen CV decreased linearly by 0.04 and 0.03 percentage units for barrows and gilts, respectively, for each

1 kg increase in live weight (Table 7). Furthermore, the predicted within-pen CV was generally higher for gilts than for barrows (Figure 4). Research on the effects of both live weight and also gender on the variation of live weight within a pen is scarce and, therefore, should be a focus of future research.

CONCLUSIONS

The results of this study suggest that pigs from modern genotypes may have the potential to be reared to heavy live weights with relatively limited effects on growth performance and carcass leanness. The relationships reported in this study can be used in economic modeling to determine of the optimum harvest weight for a given production system.

LITERATURE CITED

Amaral Filha, W. S., M. L. Bernardi, I. Wentz, and F. P. Bortolozzo. 2009. Growth rate and age at boar exposure as factors influencing gilt puberty. Livest. Sci. 120:51-57.

Augspurger, N. R., M. Ellis, D. N. Hamilton, B. F. Wolter, J. L. Beverly, and E. R. Wilson. 2002. The effect of sire line on the feeding patterns of grow-finish pigs. Appl. Anim. Behav. Sci. 75:103-114.

Cisneros F., M. Ellis, F. K. McKeith, J. McCaw, and R. L. Fernando. 1996. Influence of slaughter weight on growth and carcass characteristic, commercial cutting and curing yields, and meat quality of barrows and gilts from two genotypes. J. Anim. Sci. 74:925-933.

Correa, J. A., C. Gariepy, M. Marcoux, L. Faucitano. 2008. Effects of growth rate, sex, and slaughter weight on fat characteristics of pork bellies. Meat Sci. 80:550-554.

Ellis, M. and T. M. Bertol. 2001. Effects of slaughter weight on pork and fat quality. In Proceedings of the 2nd international virtual conference on pork quality, November-6 December 2001, Concordia, Brazil. pp 213-224.

Kanis, E., G. J. Nieuwhof, K. H. de Greef, W. van der Hel, M. W. A. Verstegen, J. Huisman, and P. van der Wal. 1990. Effect of recombinant porcine somatotropin on growth and carcass quality in growing pigs: Interactions with genotype, gender and slaughter weight. J. Anim. Sci. 68:1193-1200.

Latorre, M. A., E. Garcia-Belenguer, and L. Arino. 2008. The effects of sex and slaughter weight on growth performance and carcass traits of pigs intended for dry-cured ham from Teruel (Spain). J. Anim. Sci. 86:1933-1942.

Latorre, M. A., R. Lazaro, D. G. Valencia, P. Medel, and G. G. Mateos. 2004. The effects of gender and slaughter weight on the growth performance, carcass traits, and meat quality characteristics of heavy pigs. J. Anim. Sci. 82:526-533.

Leach, L. M., M. Ellis, D. S. Sutton, F. K. McKeith, and E. R. Wilson. 1996. The growth performance, carcass characteristics, and meat quality of halothane carrier and negative pigs. J. Anim. Sci. 74:934-943.

NRC. 1998. Nutrient Requirements of Swine (10th Ed.). National Academy Press. Washington, DC.

Schinckel, A. P., S. Pence, M. E. Einstein, R. Hinson, P. V. Preckel, J. S. Radcliffe, and B. T. Richert. 2006. Evaluation of different mixed model nonlinear equations on pigs fed low-nutrient excretion diets. Prof. Anim. Sci. 22:401-412.

Strathe, A. B., A. Danfaer, H. Sorensen, and E. Kebreab. 2010. A multilevel nonlinear mixed-effects approach to model growth in pigs. J. Anim. Sci. 88:638-649.

Steel, R. G. D. and J. H. Torrie. 1980. Principles and Procedures of Statistics: A Biometrical Approach. 2nd ed. McGraw-Hill Book Co., New York.

USDA-NASS, cited 2012. National statistics for hogs: Hogs, slaughter, commercial – slaughtered, measured in lb/head, live basis. [Available online at http://www.nass.usda.gov/Statistics_by_Subject/result.php?EC81DC9D-92A0-308E-8435- 3682E88ACFB1&sector=ANIMALS%20%26%20PRODUCTS&group=LIVESTOCK&comm=HOGS]

Wagner, J. R., A. P. Schinckel, W. Chen, J. C. Forrest, and B. L. Coe. 1999. Analysis of body composition changes of swine during growth and development. J. Anim. Sci. 77:1442-1466.

TABLES

Table 4. Least-squares means for the effect of gender on the live weight, variability in live weight, and growth rate of pigs reared to ~168 kg pen mean live weight.

Item	Gender		SEM	*P*-value
	Barrows	Gilts		
Number of observations	6	6	-	-
Body weight, kg				
Start (weaning)	5.7	5.7	0.15	0.21
Week 2	8.7	8.8	0.29	0.45
Week 4	13.6	13.8	0.37	0.44
Week 6	21.3	21.5	0.46	0.47
Week 8	31.6	32.0	0.71	0.38
Week 10	44.5	44.5	0.94	0.92
Week 12	59.8	58.7	1.26	0.22
Week 14	76.3	74.0	1.61	0.04
Week 16	92.6	89.5	1.60	0.03
Week 18	108.2	104.4	1.53	0.01
Week 20	123.8	118.7	1.74	0.01
Week 22	136.6	131.6	1.75	0.004
Week 24	149.1	144.5	1.91	0.003
End of study	167.8	167.2	1.40	0.79
Coefficient of variation (within-pen), %				
Start (weaning)	20.5	20.4	0.86	0.88
Week 14	11.7	12.4	0.47	0.24
Week 16	10.2	11.4	0.33	0.01
Week 18	9.4	10.6	0.48	0.01
Week 20	8.7	10.3	0.44	0.01
Week 22	8.2	10.0	0.53	0.04
Week 24	8.1	9.7	0.63	0.10
End of study	7.9	9.4	0.51	0.06
Days to end of study	192.0	196.7	3.50	0.17
Average daily gain, kg				
Start - week 2	0.24	0.24	0.015	0.46
Week 2 - week 4	0.35	0.36	0.009	0.64
Week 4 - week 6	0.55	0.55	0.013	0.53
Week 6 - week 8	0.74	0.74	0.022	0.89
Week 8 - week 10	0.92	0.89	0.018	0.06
Week 10 - week 12	1.09	1.02	0.026	0.01
Week 12 - week 14	1.17	1.09	0.030	0.001
Week 14 - week 16	1.17	1.11	0.020	0.09
Week 16 - week 18	1.12	1.06	0.018	0.04
Week 18 - week 20	1.11	1.03	0.027	0.01
Week 20 - week 22	0.91	0.92	0.025	0.82
Week 22 - week 24	0.90	0.90	0.019	0.92
Week 24 - end of study	0.83	0.82	0.025	0.95
Start - end of study	0.84	0.81	0.014	0.04
Morbidity and mortality, %	3.33	7.50	-	0.09

Table 5. Least-squares means for the effect of gender on the feed intake and feed efficiency of pigs reared to ~168 kg pen mean live weight.

	Gender			
Item	Barrows	Gilts	SEM	*P*-value
Number of observations	6	6	-	-
Average daily feed intake, kg				
Start - week 2	0.29	0.29	0.021	0.81
Week 2 - week 4	0.53	0.55	0.012	0.10
Week 4 - week 6	0.88	0.91	0.018	0.21
Week 6 - week 8	1.33	1.36	0.030	0.38
Week 8 - week 10	1.83	1.78	0.037	0.10
Week 10 - week 12	2.47	2.26	0.047	0.01
Week 12 - week 14	2.97	2.64	0.067	0.001
Week 14 - week 16	3.23	2.89	0.034	0.001
Week 16 - week 18	3.40	3.06	0.024	<0.001
Week 18 - week 20	3.50	3.16	0.054	0.003
Week 20 - week 22	3.34	3.16	0.039	<0.001
Week 22 - week 24	3.31	3.26	0.037	0.13
Week 24 - end of study	3.18	3.08	0.055	0.29
Start - end of study	2.36	2.24	0.018	0.001
Gain:feed, kg:kg				
Start - week 2	0.834	0.845	0.0258	0.64
Week 2 - week 4	0.666	0.656	0.0142	0.64
Week 4 - week 6	0.617	0.610	0.0057	0.48
Week 6 - week 8	0.553	0.544	0.0114	0.39
Week 8 - week 10	0.505	0.501	0.0042	0.22
Week 10 - week 12	0.443	0.450	0.0046	0.08
Week 12 - week 14	0.396	0.414	0.0049	0.03
Week 14 - week 16	0.361	0.383	0.0051	0.03
Week 16 - week 18	0.328	0.347	0.0054	0.04
Week 18 - week 20	0.318	0.325	0.0056	0.45
Week 20 - week 22	0.273	0.291	0.0069	0.13
Week 22 - week 24	0.271	0.277	0.0053	0.47
Week 24 - end of study	0.260	0.267	0.0040	0.26
Start - end of study	0.357	0.364	0.0037	0.08

Table 6. Least-squares means for the effect of gender on the live animal ultrasound measures of pigs reared to ~168 kg pen mean live weight.

	Gender			
Item	Barrows	Gilts	SEM	*P*-value
Number of observations	6	6	-	-
Backfat depth, cm				
Week 14	16.6	14.9	0.41	0.03
Week 16	18.6	15.9	0.41	0.01
Week 18	22.7	19.4	0.53	0.01
Week 20	25.1	20.7	0.53	0.002
Week 22	25.9	22.1	0.38	0.001
Week 24	29.5	25.6	0.58	0.003
End of study	33.4	30.2	0.88	0.03
Longissimus muscle area, sq. cm				
Week 14	31.0	31.1	0.48	0.76
Week 16	34.2	34.8	0.46	0.08
Week 18	39.9	40.4	0.51	0.11
Week 20	45.7	46.2	0.55	0.24
Week 22	48.2	49.3	0.63	0.03
Week 24	50.4	52.1	0.63	0.01
End of study	51.9	54.6	0.49	0.01
Predicted carcass lean weight, kg[1]				
Week 14	37.3	37.0	0.58	0.48
Week 16	42.9	42.8	0.49	0.71
Week 18	48.4	48.2	0.58	0.19
Week 20	54.3	54.1	0.69	0.45
Week 22	59.1	59.1	0.73	0.86
Week 24	62.8	63.1	0.83	0.10
End of study	68.1	69.8	0.71	0.13

[1]Predicted carcass lean weight, kg = 8.9 + 0.347 * BW (kg) – 0.379 * 10th rib backfat (mm) + 0.269 * *Longissimus* muscle area (cm^2) [Schinckel, personal communication; data used to develop equation reported in Schinckel et al., 2001; JAS].

Table 7. Summary of key regression equations.[a]

Dependent variable	Independent variable	Dependent variable statistics: Mean	Dependent variable statistics: Standard deviation	Parameter estimates[b]: Intercept	Live wt.	Live wt.^{2}	Live wt.^{3}	R^2	RSD[c]
Gender									
Barrows									
Instantaneous average daily gain, kg	Live weight, kg	0.84	0.298	0.012	0.0348	-0.00031	0.00000077	0.95	0.07
Instantaneous average daily feed intake, kg	Live weight, kg	2.35	1.130	-0.132	0.0629	-0.00027	NS	0.99	0.12
Instantaneous gain:feed, kg:kg	Live weight, kg	0.434	0.1761	0.769	-0.0071	0.00003	NS	0.93	0.05
Within-pen coefficient of variation, %	Live weight, kg	9.04	1.775	13.963	-0.0391	NS	NS	0.49	1.27
Ultrasound measurements (10^{th} rib)									
Backfat depth, mm	Live weight, kg	25.3	5.79	2.352	0.1820	NS	NS	0.92	1.68
Longissimus muscle area, sq. cm	Live weight, kg	43.9	7.75	-7.038	0.5942	-0.00142	NS	0.97	1.27
Predicted carcass lean weight, kg[d]	Live weight, kg	54.5	10.59	11.348	0.3433	NS	NS	0.99	0.81
Gilts									
Instantaneous average daily gain, kg	Live weight, kg	0.81	0.269	0.039	0.0329	-0.00031	0.00000081	0.94	0.07
Instantaneous average daily feed intake, kg	Live weight, kg	2.24	1.025	0.019	0.0533	-0.00022	NS	0.98	0.13
Instantaneous gain:feed, kg:kg	Live weight, kg	0.436	0.1727	0.762	-0.0067	0.00002	NS	0.91	0.05
Within-pen coefficient of variation, %	Live weight, kg	10.39	1.404	14.262	-0.0312	NS	NS	0.49	1.01
Ultrasound measurements (10^{th} rib)									
Backfat depth, mm	Live weight, kg	22.3	5.43	1.270	0.1696	NS	NS	0.93	1.48
Longissimus muscle area, sq. cm	Live weight, kg	45.3	8.42	-6.806	0.6069	-0.00141	NS	0.98	1.26
Predicted carcass lean weight, kg[d]	Live weight, kg	55.2	11.07	3.586	0.4912	-0.00056	NS	1.00	0.69

[a]Instantaneous ADG, ADFI, and G:F were based on interim measurements from start to end of study and all other variables were based on interim measurements from week 14 post-weaning to end of study.

[b]NS = not significant (i.e., $P > 0.05$).

[c]Residual standard deviation.

[d]Predicted carcass lean weight, kg = 8.9 + 0.347 * BW (kg) – 0.379 * 10^{th} rib backfat (mm) + 0.269 * *Longissimus* muscle area (cm^2) [Schinckel, personal communication; data used to develop equation reported in Schinckel et al., 2001; JAS].

FIGURES

Figure 1. Regression of instantaneous average daily gain against live weight for barrows and gilts.

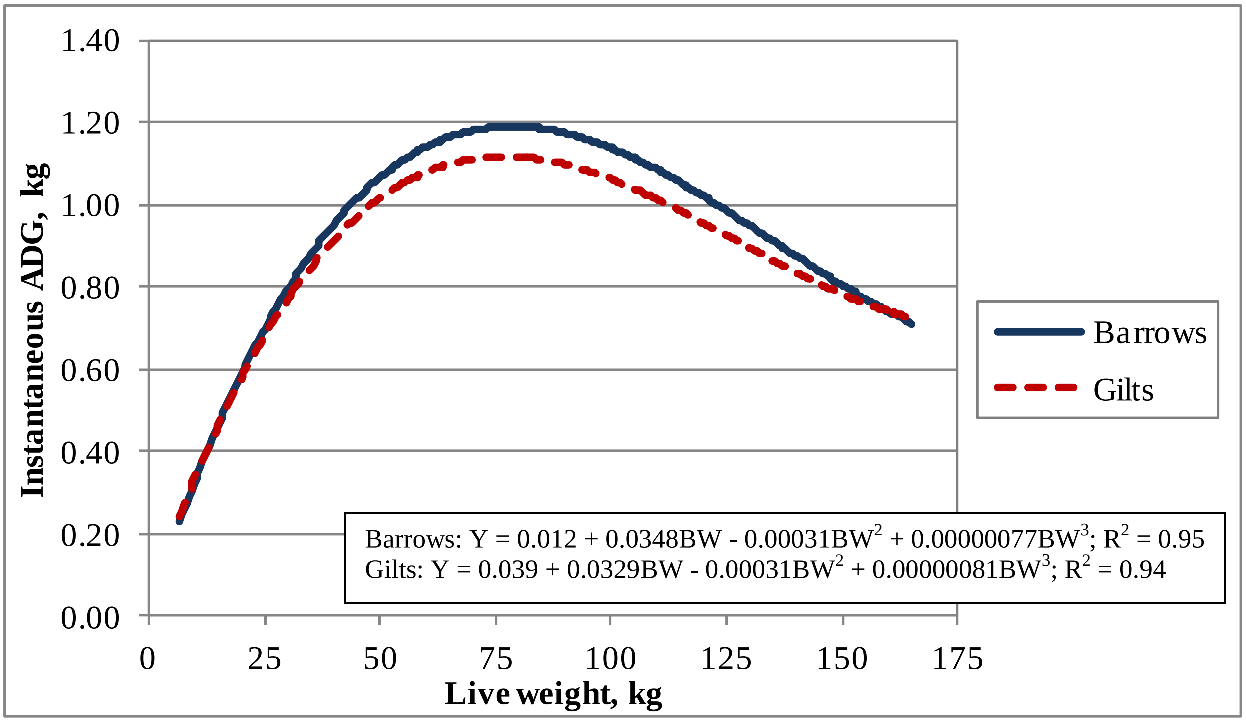


Figure 2. Regression of instantaneous average daily feed intake against live weight for barrows and gilts.

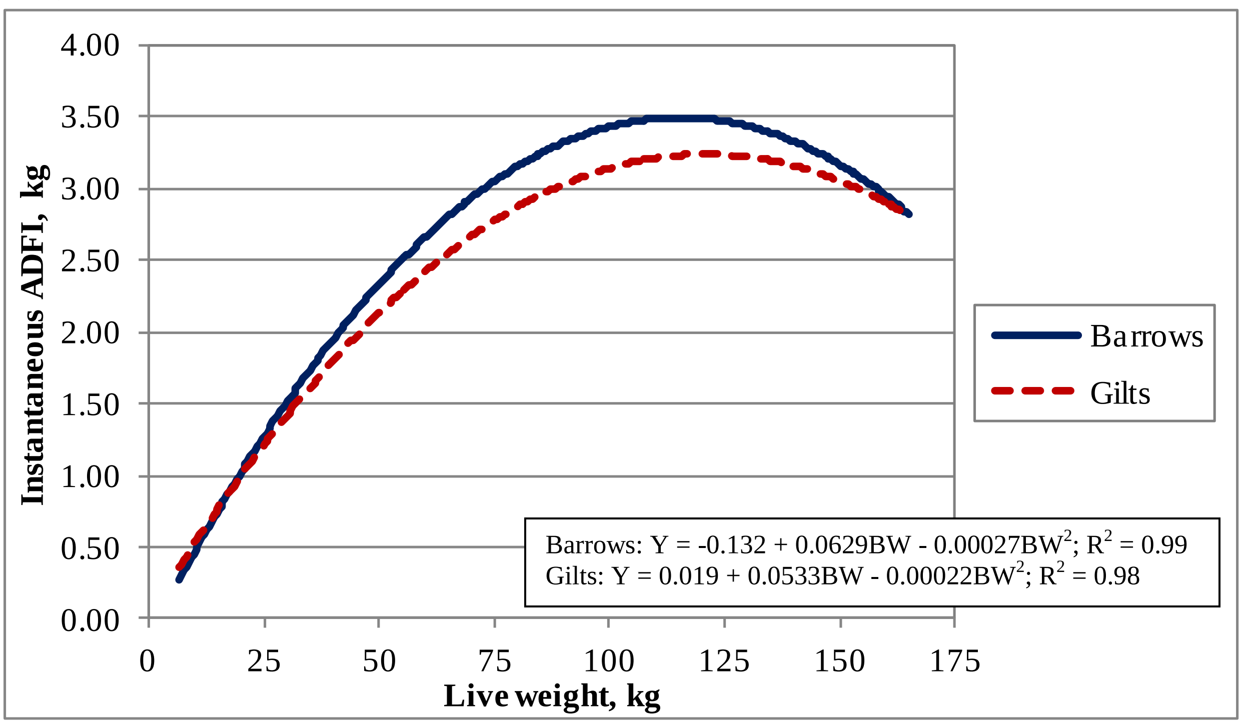


Figure 3. Regression of instantaneous gain:feed against live weight for barrows and gilts.

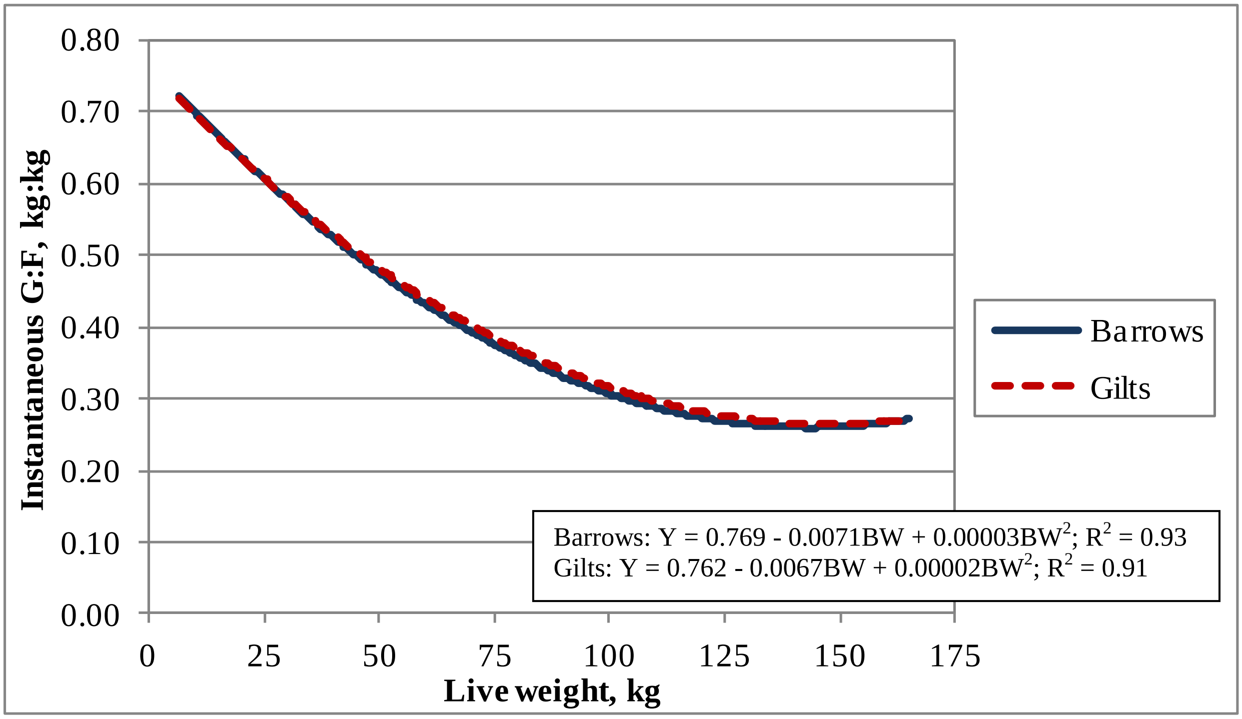


Figure 4. Regression of within-pen coefficient of variation against live weight for barrows and gilts.

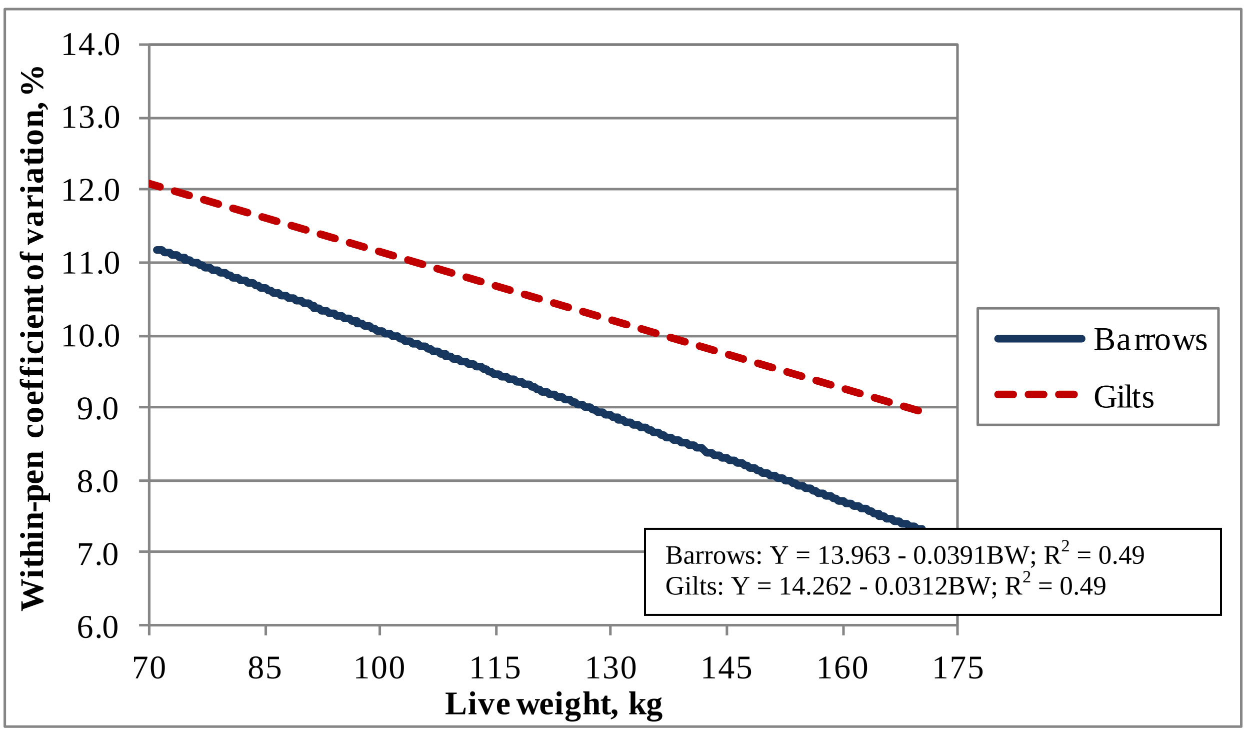


Figure 5. Regression of 10th rib backfat depth against live weight for barrows and gilts.

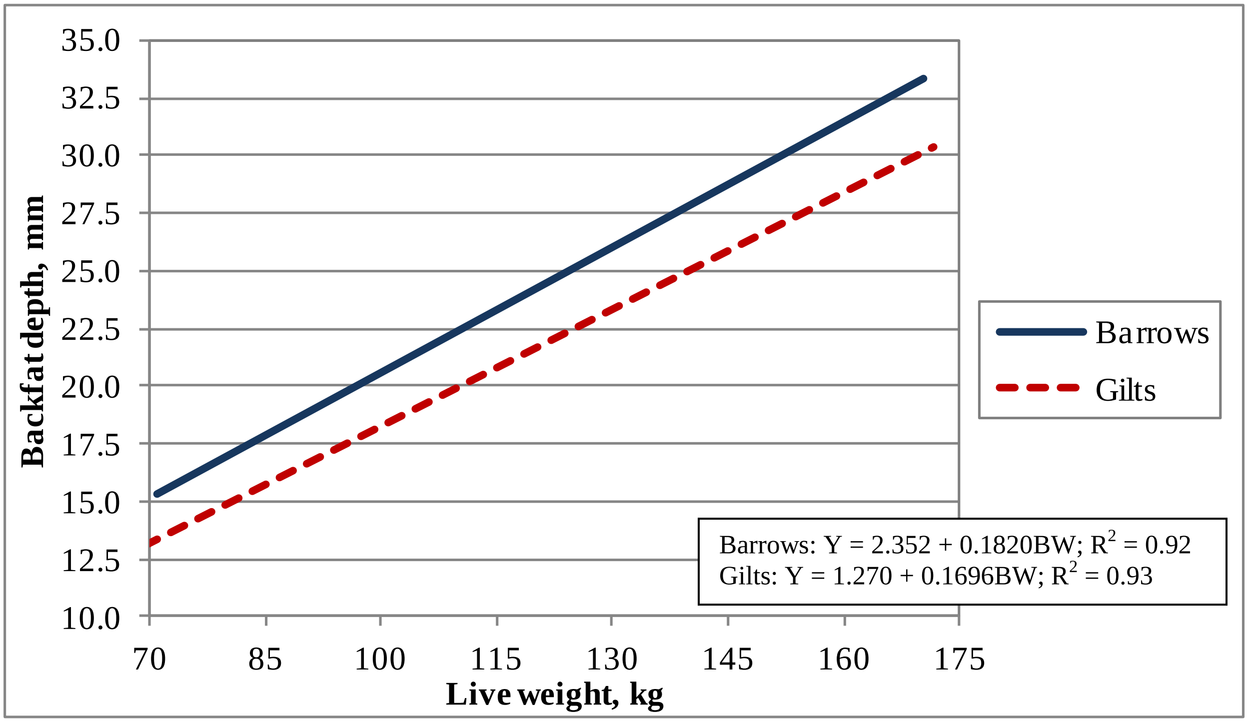


Figure 6. Regression of 10th rib *Longissimus* muscle area against live weight for barrows and gilts.

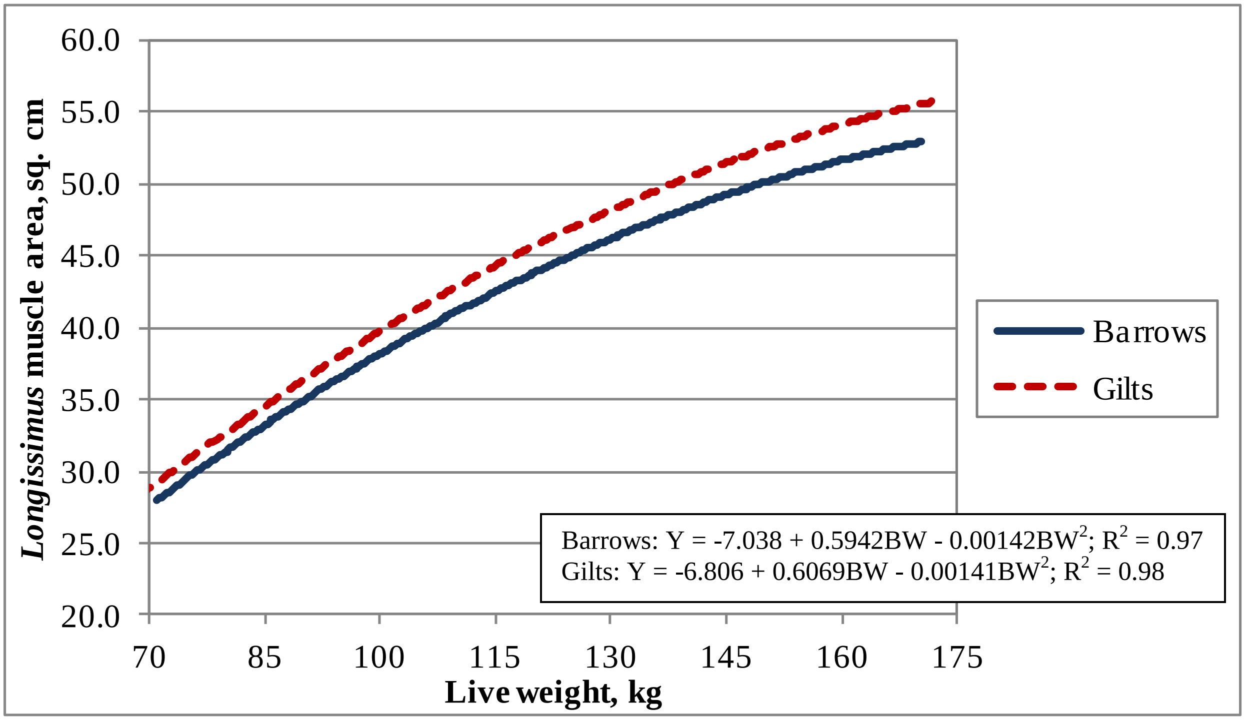
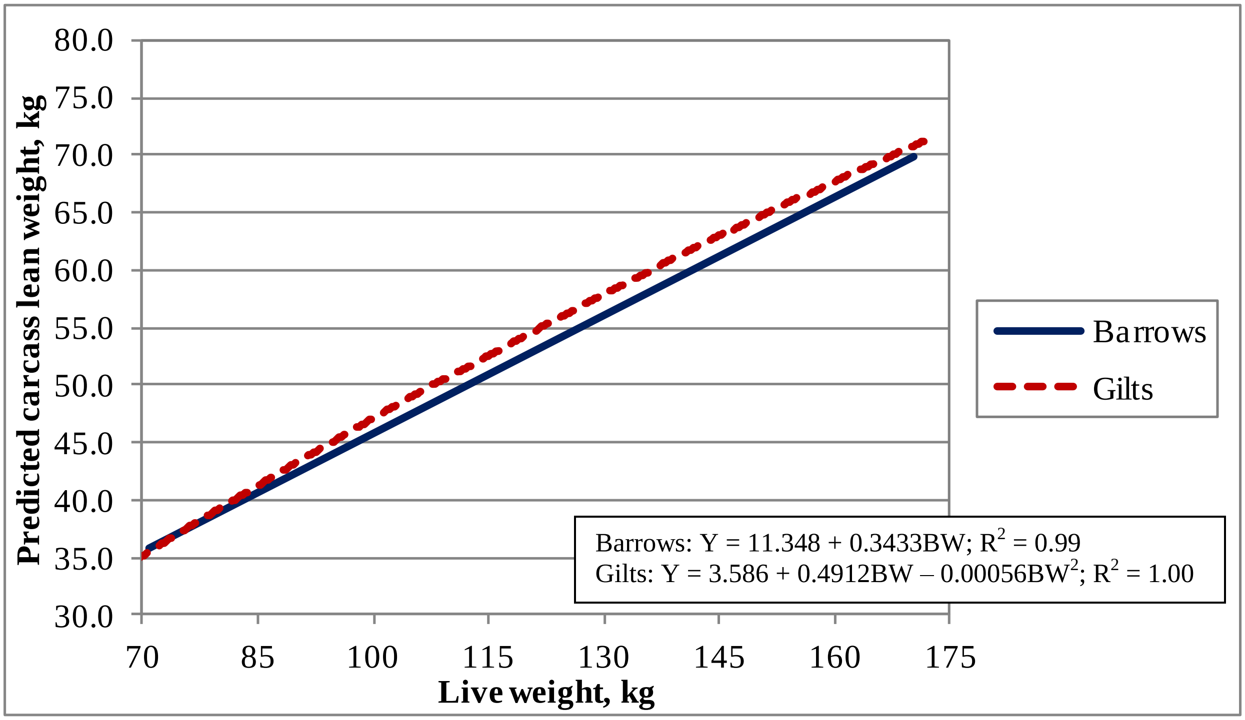


Figure 7. Regression of predicted carcass lean weight against live weight for barrows and gilts.



CHAPTER 3: IMPACT OF INCREASED HARVEST WEIGHT ON OVERALL GROWTH PERFORMANCE AND CARCASS CHARACTERISTICS OF PIGS.

ABSTRACT

The effects of gender and harvest weight were evaluated in a commercial wean-to-finish facility in a study that used a RCBD with a 2 × 7 factorial arrangement of the following treatments: 1) Gender (barrows and gilts) and 2) Harvest Weight (113, 125, 136, 147, 159, 170, and 181 kg; which represents the live weight of each individual pig within the pen). The study was carried out using 8 replicates with 2,240 pigs in 112 single-gender pens of 20 pigs from weaning to the designated harvest weight treatment level. Pigs had ad libitum access to feed and water and were provided a floor space of 1.06 m^2/pig. Data were analyzed using the PROC MIXED procedure of SAS and regression equations were developed between the mean live weight at the end of study and all measures of overall growth performance and carcass characteristics. Overall ADG, carcass ADG, and overall ADFI was 3.0, 3.3, and 5.7% higher ($P \leq 0.05$), respectively, for barrows compared to gilts. There was a Gender by Harvest Weight interaction ($P \leq 0.05$) for both overall G:F and carcass G:F, with gilts having a higher ($P \leq 0.05$) overall and carcass G:F than barrows at every Harvest Weight except for the heaviest and lightest treatment levels, at which gilts were similar ($P > 0.05$) to barrows. Gilts had 12.4% less ($P \leq 0.05$) backfat depth and 3.2 and 2.1% higher ($P \leq 0.05$) *Longissimus* muscle area and depth, respectively, and 2.9% higher ($P \leq 0.05$) predicted carcass lean content than barrows. There was no effect ($P > 0.05$) of Gender on carcass yield. Overall ADG and carcass ADG were highest ($P \leq 0.05$) for the middle Harvest Weight levels and lowest for the lightest and heaviest 2 Harvest Weight levels. As the mean live weight at the end of study increased, overall ADFI, backfat depth, and carcass yield increased linearly ($P \leq 0.05$) for both genders, overall G:F, carcass G:F, and predicted carcass lean content decreased linearly ($P \leq 0.05$) for both genders, and

Longissimus muscle depth and area increased linearly ($P \leq 0.05$) for barrows and quadratically ($P \leq 0.05$) for gilts. The results of this study confirm that pigs can be reared to heavier harvest weights with relatively limited impact on overall growth performance or carcass leanness.

INTRODUCTION

There are economic reasons for increasing the harvest weight of pigs in most swine industries. These include the potential for reduced overhead costs for producers, packers, and processers (Ellis and Bertol, 2001). Continued genetic improvement in growth performance and carcass leanness is another potential reason for continual increases in harvest weight. However, a detailed understanding of the incremental changes in growth performance and carcass characteristics as harvest weight is increased is required to identify the economic optimum live weight at which to harvest pigs. A number of studies have evaluated the growth performance and carcass characteristics of pigs reared to heavier harvest weights (Leach et al., 1996; Cisneros et al., 1996; Wagner et al., 1999); however, these studies were typically carried out in a research setting with small numbers of pigs which is different than that of a commercial production system. Therefore, the objective of this research was to determine the impact of increased harvest live weight on the overall growth performance and carcass characteristics of barrows and gilts reared in a commercial wean-to-finish facility.

MATERIALS AND METHODS

The study was conducted in a standard wean-to-finish facility at the The Maschhoffs' Georgia Technology Center located near New Minden, IL. The experimental protocol was approved by the University of Illinois Institutional Animal Care and Use Committee (IACUC #10216).

Experimental Design and Treatments. The study was carried out as a randomized complete block design with a 2 × 7 factorial arrangement of the following treatments: 1) Gender (barrows and gilts) and 2) Harvest Weight (113, 125, 136, 147, 159, 170, and 181 kg; representing the live weight of each individual pig within the pen).

Animals and Allotment. A total of 2,240 pigs (112 single-gender pens of 20 animals; 8 pens per Gender by Harvest Weight treatment subclass) were used. The pigs used in the study were the progeny of PIC 359 sires mated to either PIC C22 or PIC C29 dams (PIC, Hendersonville, KY). Dam line was not taken into account in the allotment of pigs to the study because the litter of origin of the pigs was unknown. Immediately following weaning, pigs were moved to the test facility and weighed individually, tagged, and sorted into outcome groups of 7 barrows and 7 gilts with similar body weight. Within each outcome group, barrows and gilts were randomly allotted to 7 barrow and 7 gilt pens, respectively. This process was repeated until there were 20 barrows or 20 gilts in each pen. Pens within gender were randomly allotted to Harvest Weight treatment and immediately started on test.

Housing and Diets. Pigs were housed in a wean-to-finish building that had fully slatted concrete flooring and was tunnel ventilated. Pen divisions consisted of gates with horizontal steel rods and pen dimensions (length x width) were 7.16 x 3.05 m, which provided a floor space of 1.06 m^2/pig. This floor space was predicted, based on previous research that was carried out to lighter final live weights, to have no impact on growth performance. There have been no studies carried out to determine the relationship between floor space and growth performance across the range of weights evaluated in this study. In the event of a mortality or removal of a morbid animal during the study, pen size was adjusted using a moveable partition to maintain the correct floor space. Air temperature was maintained using thermostatically controlled heaters and fan ventilation. The thermostat was maintained at 27° C for the first week post-weaning and lowered in subsequent weeks until it reached 18° C where it was maintained for the duration of the study. During the first 14 days post-weaning, supplemental heat was provided by one heat reflective heat lamp (125 W) per pen suspended 75 cm above the floor. Under hot conditions when the ambient room temperature reached 29.4° C, water sprinklers were used in an attempt to cool the pigs.

Each pen was equipped with one 5-hole wet/dry box feeder (Feed Ease Wet/Dry Feeder, A. J. O'Mara Group, Lyons, NE) mounted in the fence line. One feeder hole was covered, providing only 4 holes in each feeder which provided 142.2 cm of total feeder trough space (7.1 cm/pig). An additional water cup was available in each pen. Pigs had ad libitum access to feed and water. An 8-phase dietary program was used and diets were formulated to meet or exceed NRC (1998) recommendations for nutrient requirements of pigs across the weight range evaluated. The final dietary phase, which was fed from approximately 115 kg live weight to the end of test, was formulated to the requirement of a 115 kg pig.

Study Period and End of Test Procedures. The end of test for all pens was when the lightest pigs in the pen reached the specific treatment weight and were sent for harvest. Within each pen, pigs were sent for harvest in 8 groups. The first 7 groups consisted of 6 groups of 2 pigs and 1 group of 4 pigs, which was taken off test and shipped for harvest between the 3^{rd} and 5^{th} harvest groups. The last group had all of the remaining pigs in the pen (maximum of 4). Within a Harvest Weight treatment level, the heaviest 2 pigs in each pen were removed when the pen reached the desired mean live weight, which depended on treatment (i.e., 99.8, 110.1, 119.1, 130.5, 139.3, 149.7, and 157.9 kg for the lightest to heaviest Harvest Weight treatment levels, respectively; Table 8). The number of days between groups being sent for harvest varied across the Harvest Weight treatment levels (4.2, 4.0, 4.4, 5.4, 6.5, 8.0, and 8.3 days for the lightest to heaviest Harvest Weight treatment levels, respectively; Table 8) and was determined for each level using the average within-pen variation in live weight and projected average daily gain of all the pens within that treatment group. Within a Harvest Weight treatment level, the average within-pen variation in live weight was obtained by collecting individual pig weights for all pens at once approximately 2 weeks prior to the projected date of harvest of the first pigs from the pens.

Growth and Carcass Measurements. Pigs were weighed individually at the start and end of test and group weights were collected every 2 weeks from the start of the study to the day the first pigs were removed from the pen for harvest. Feed data were collected using a computerized feed-mixing (L.O.M.A.N. Systmetechovik, Bremerhaven, Germany) and feed delivery (ASA International, Medolago, Italy) system that recorded the weight of feed delivered to each feeder. The amount of feed left in the feeder was recorded for each pen at the time that the group weights were collected. Pigs experiencing either health problems or injuries that did not respond to treatment were removed from the study and the date of, pig weight at, and reason for removal were recorded; the weight of pigs removed was included in the calculation of growth rate and gain:feed ratio. The day prior to shipment for harvest, each pig was scanned using an Aloka Model 500V B-mode ultrasound scanner fitted with an Aloka 5011 probe (Corometrics Medical Systems, Wallingford, CT) at the time of weighing with the image being taken transversely over the tenth rib. Backfat depth and *Longissimus* muscle depth and area were manually measured on the image.

Pigs were harvested at Pine Ridge Farms (Des Moines, IA) using standard procedures. The skin, head, and front and hind feet were removed from the carcass immediately after harvest and prior to the measurement of hot carcass weight.

Statistical Analysis. Data were analyzed as a randomized complete block design with pen as the experimental unit. All data were tested for normality using the PROC UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC). Morbidity and mortality data were not normally distributed and were analyzed using a Chi-square rank-based test (Steel and Torrie, 1980) using the PROC RANK procedure of SAS. Data meeting the criteria for normality were analyzed using the PROC MIXED procedure of SAS with the model including the fixed effects of Gender and Harvest Weight and their interaction and the random effect of block. Least-squares means were compared using the PDIFF option of SAS and differences between means were considered significant if $P \leq 0.05$. Polynomial regression equations were developed between the mean live weight at the end of study and overall ADG, ADFI, and G:F, carcass ADG and G:F, backfat depth and *Longissimus* muscle depth and area measured ultrasonically at the 10^{th} rib, and predicted carcass lean content (%). Polynomial equations were also developed between the mean harvest live weight for each pen and carcass yield. All regression equations were developed using the PROC MIXED procedure of SAS and the model included the random effect of block. The quadratic and cubic coefficients were only included in the model if they were found significant ($P \leq 0.05$) by the log-likelihood test. The coefficient of determination (R^2) and residual standard deviation (RSD) were calculated for each regression equation.

RESULTS AND DISCUSSION

Growth Performance. Growth performance data are presented in Table 9 and regression equations for growth performance are presented in Table 10 and illustrated graphically in Figures 8 to 10.

Effect of Gender:

Live weight at the end of the study was 0.9 kg higher ($P = 0.04$) for barrows than gilts (Table 9). This difference was not intended and is the result of errors in the projection of the weights of pigs to be sent for harvest, which was primarily due to highly variable growth rates during this period. Within-pen coefficient of variation (CV) was higher for gilts compared to barrows at the start ($P < 0.001$) but not at the end ($P > 0.05$) of study (Table 9). There was no effect ($P > 0.05$) of gender on morbidity and mortality (Table 9). This is in contrast to the results of Chapter 2 of this thesis, which reported a higher within-pen CV for gilts than barrows at the end of the study. Overall ADG, carcass ADG, and overall ADFI was 3.0, 3.3, and 5.7% higher ($P < 0.001$), respectively, for barrows compared to gilts (Table 9). These results are consistent with other studies that compared the growth and feed intake of barrows and gilts (Cisneros et al., 1996; Wagner et al., 1999; Latorre et al., 2008). There was a Gender by Harvest Weight interaction ($P \leq 0.05$) for both overall G:F and carcass G:F (Table 9). On both a live- and carcass-weight basis, gilts had higher ($P \leq 0.05$) G:F from start to end of study that barrows at every Harvest Weight apart from the heaviest and lightest treatment levels, at which gilts were similar ($P > 0.05$) to barrows. Similar feed efficiency at the lightest Harvest Weight treatment level can be explained by the fact that differences in growth performance between genders typically does not occur during the early stages of growth (Brumm, 2004). However, it is not clear why feed efficiency was similar for barrows and gilts at the heaviest Harvest Weight treatment level.

Effect of Harvest Weight:

As expected, live weight at the end of the study and, consequently, the time in days to the removal of the first pig from the pen for harvest, increased ($P \leq 0.05$) as Harvest Weight increased (Table 9). Pigs on the 170 and 181 kg Harvest Weight treatment levels grew slower than expected towards the end of the study and, as a result, the mean live weight at the end of the study was 3.7 and 4.2 kg, respectively, lower than the targeted Harvest Weight treatment level. Morbidity and mortality was not affected ($P > 0.05$) by Harvest Weight (Table 9).

There were no ($P > 0.05$) linear, quadratic, or cubic relationships between the mean live weight at the end of study and overall ADG for barrows and carcass ADG for both barrows and gilts (Table 10). There was a linear decrease ($P \leq 0.05$) in overall ADG for gilts as live weight at harvest increased; however, the relationship was weak ($R^2 = 0.33$; Table 10). In general, overall ADG and carcass ADG were highest ($P \leq 0.05$) for the middle Harvest Weight levels and lowest for the lightest and heaviest 2 Harvest Weight levels (Table 9). Studies evaluating harvest weights ranging from 80 to 160 kg have shown either similar (Cisneros et al., 1996; Latorre et al., 2003) or decreased (Ellis et al., 1996; Leach et al., 1996; Latorre et al., 2004; Latorre et al., 2008) overall ADG as harvest weight increased.

Overall ADFI for barrows and gilts increased linearly ($P \leq 0.05$) by 0.007 and 0.006 kg, respectively, for each 1 kg increase in live weight at the end of study (Table 10). Similarly, Cisneros et al. (1996) reported a linear increase in overall ADFI of 0.01 kg per 1 kg increase in harvest weight from a starting weight of 60 kg to harvest weights of 100, 115, 130, 145, and 160 kg. Other studies evaluating harvest weights ranging from 116 to 140 kg reported no effect of harvest weight on overall ADFI (Latorre et al., 2004; Latorre et al., 2008). In the current study, increasing the live weight at end of study had a negative impact on feed efficiency as overall G:F and carcass G:F decreased linearly ($P \leq 0.05$) for both barrows and gilts (Table 10). Leach et al. (1996) and Latorre et al. (2008) reported a linear decrease in overall G:F of 0.001 units for each 1 kg increase in harvest weights from 110 and 120 kg, respectively, to 140 kg. Conversely, Cisneros et al. (1996) reported no effect of harvest weight on overall feed efficiency. Between studies, the differences in overall ADG, ADFI, and G:F between harvest weights will depend on the weight at the start of the study.

In the current study, the heaviest pigs were removed from pens and sent for harvest first in order to reduce the variation in harvest live weight. While this is commonly done in commercial production, it does potentially impact the growth performance of the remaining pigs in the pen. A number of studies have shown increased ADG and ADFI for the remaining animals after the heaviest pigs were removed for harvest (Bates and Newcomb, 1997; DeDecker et al., 2002; DeDecker et al., 2005). Bates and Newcomb (1997) and DeDecker et al. (2002) reported no effect of removing 50 and 30%, respectively, of the heaviest pigs from the pen on the feed efficiency of the remaining animals; however, DeDecker et al. (2005) reported higher feed efficiency for the remaining pigs for pens with 25 and 50% of the heaviest pigs removed compared to pens with no pigs removed. No studies have evaluated the impact of live weight on the response to removal of pigs from pens and this could be an area of future research.

Live Animal Ultrasound Measurements and Carcass Characteristics. Live animal ultrasound measurements and carcass characteristics are presented in Table 11 and the regression equations are presented in Table 10 and illustrated graphically in Figures 11 to 15.

<u>Effect of Gender:</u>

On average gilts, compared to barrows, had 12.4% less ($P \leq 0.05$) backfat depth and 3.2 and 2.1% higher ($P \leq 0.05$) *Longissimus* muscle area and depth, respectively, measured ultrasonically at the 10th rib (Table 11). Additionally, gilts had 2.3 and 2.9% higher ($P \leq 0.05$) predicted carcass lean weight and content, respectively, than barrows (Table 11). These results are comparable to other studies who have evaluated barrows and gilts grown to heavier live weights (Cisneros et al., 1996; Wagner et al., 1999; Latorre et al., 2008). There was no effect ($P > 0.05$) of Gender on carcass yield. A number of studies have reported no effect of gender on carcass yield (Cisneros et al., 1996; Hamilton et al., 2000; Hamilton et al., 2002; Hyun et al., 2004; Latorre et al., 2008); however, all of these studies have shown a numerical advantage in carcass yield for the barrow compared to the gilt. A couple of other studies have reported higher carcass yield for gilts than barrows (Ellis et al., 1996; Latorre et al., 2004). One possible explanation for the differing results may be the method used to trim the carcass at harvest.

Effect of Harvest Weight:

For the regression analysis, as the mean live weight at the end of study increased, backfat depth (Figure 11) increased linearly ($P \leq 0.05$) for both barrows and gilts, *Longissimus* muscle area (Figure 12) and depth (Figure 13) increased linearly ($P \leq 0.05$) for barrows and quadratically ($P \leq 0.05$) for gilts, and predicted carcass lean content (Figure 14) decreased linearly ($P \leq 0.05$) for both barrows and gilts (Table 10). Backfat depth increased by 0.18 and 0.20 mm per 1 kg increase in the mean live weight at the end of study for barrows and gilts, respectively (Table 10 and Figure 11). Predicted carcass lean content decreased by 0.11 and 0.13 percentage units for barrows and gilts, respectively, for each 1 kg increase in the mean live weight at the end of the study (Table 10 and Figure 14).

Several studies have evaluated the impact of increasing harvest weight on carcass characteristics. Wagner et al. (1999) evaluated harvest weights from 25 to 152 kg and reported a linear increase in backfat depth and quadratic increases in *Longissimus* muscle area and fat free lean weight as harvest weight increased. A number of studies that have evaluated harvest weights between 100 and 160 kg have reported an increase in backfat depth ranging from 0.16 to 0.25 mm per 1 kg increase in harvest weight (Cisneros et al., 1996; Leach et al., 1996; Čandek-Potokar et al., 1998; Latorre et al., 2004; Latorre et al., 2008). Cisneros et al. (1996) reported a linear increase in *Longissimus* muscle area of 0.18 cm^2 per 1 kg increase in harvest weight as harvest weight increased from 100 kg to 160 kg. A study evaluating harvest weights of 100 and

130 kg reported 9.4 cm^2 larger *Longissimus* muscle area for pigs harvested at 130 kg compared to 100 kg (Čandek-Potokar et al., 1998). Similarly, Geri et al. (1990) reported *Longissimus* muscle areas of 48.4 and 68.1 cm^2 for pigs harvested at 95 and 145 kg, respectively. In contrast, Leach et al. (1996) reported no effect of increasing harvest weight from 110 to 140 kg on *Longissimus* muscle area or depth. The change in both fat depth and muscle depth and area as live weight at harvest increases are likely to depend on the genetic potential for lean growth and feed intake of the pigs used in the study.

The mean harvest live weights (Table 11) were slightly different from the live weight at end of study (Table 9) due to missing carcass data for a few of the pigs. There was a Gender by Harvest Weight interaction ($P \leq 0.05$) for harvest live weight and hot carcass weight (Table 11). This interaction was not intended and was the result of incorrectly predicting growth rates at the time the pigs were being sent for harvest, which resulted in differences in weights between genders within Harvest Weight treatment levels. However, the largest difference was 2.7 and 2.5 kg for harvest live weight and hot carcass weight, respectively (Table 11). There was a linear increase ($P \leq 0.05$) in carcass yield of 0.05 and 0.04 percentage units for each 1 kg increase in mean harvest live weight (Table 10 and Figure 15). A number of other studies have shown a linear increase in carcass yield as harvest weight increased (Cisneros et al., 1996; Latorre et al., 2004; Latorre et al., 2008). Interestingly, Wagner et al. (1999) reported a quadratic increase in carcass yield as live weight at harvest increased from 25 to 152 kg; however, these results are not directly comparable to those of the current study due to the much lower harvest weights that were evaluated in the study of Wagner et al (1999). Gu et al. (1992) reported that between live weights of 59 and 127 kg the rate of growth, relative to live weight, was greater for fat and lean than that of bone and skin and was generally greater for fat than lean. Non-carcass growth, such as visceral mass, must also be considered; however, few studies have reported on the effect of harvest weight on visceral mass. Nevertheless, the rate of growth of the carcass relative to live weight for harvest weight pigs is likely influenced mostly by fat growth and secondly by lean growth. As a result, the relationship between carcass yield and live weight would be expected to be similar to the relationship between fat mass and live weight. Fat mass was not measured in the current study; however, backfat depth should be highly correlated with total fat mass in the carcass. The results of the current study support the theory that carcass yield is primarily influenced by fat accretion as both backfat depth and carcass yield increased linearly as the live weight at harvest increased.

CONCLUSIONS

The results of this study confirm that pigs can be reared to heavier harvest weights with relatively limited effects on overall growth performance or carcass leanness. These results can be incorporated into an economic model to determine the optimum weight at which to harvest pigs.

LITERATURE CITED

Bates, R. O., and M. D. Newcomb. 1997. Removal of market ready pen mates improved growth rate of remaining pigs. J. Anim. Sci. 78(Suppl. 2): 34. (Abstr.)

Brumm, M. C. 2004. The effect of space allocation on barrow and gilt performance. J. Anim. Sci. 82:2460-2466.

Čandek-Potokar, M., B. Žlender, L. Lefaucheur, and M. Bonneau. 1998. Effects of age and/or weight at slaughter on *longissimus dorsi* muscle: Biochemical traits and sensory quality in pigs. Meat Sci. 48:287-300.

Cisneros F., M. Ellis, F. K. McKeith, J. McCaw, and R. L. Fernando. 1996. Influence of slaughter weight on growth and carcass characteristic, commercial cutting and curing yields, and meat quality of barrows and gilts from two genotypes. J. Anim. Sci. 74:925-933.

DeDecker, J. M., M. Ellis, B. F. Wolter, B. P. Corrigan, and S. E. Curtis. 2002. Effect of removing pigs from a pen a slaughter weight on the growth performance of the remaining animals. In Proc. 2002 Br. Soc. Anim. Sci. Mtg., York, U. K.

DeDecker, J. M., M. Ellis, B. F. Wolter, B. P. Corrigan, S. E. Curtis, E. N. Parr, and D. M. Webel. 2005. Effects of proportion of pigs removed from a group and subsequent floor space on growth performance of finishing pigs. J. Anim. Sci. 83:449-454.

Ellis, M., A. J. Webb, P. J. Avery, and I. Brown. 1996. The influence of terminal sire genotype, sex, slaughter weight, feeding regime and slaughter-house on growth performance and carcass and meat quality in pigs and on the organoleptic properties of fresh pork. Anim. Sci. 62:521-530.

Ellis, M. and T. M. Bertol. 2001. Effects of slaughter weight on pork and fat quality. In Proceedings of the 2nd international virtual conference on pork quality, November-6 December 2001, Concordia, Brazil. pp 213-224.

Geri, G., O. Franci, B. M. Poli, G. Campodoni, and A. Zappa. 1990. Relationships between adipose tissue characteristics of newborn pigs and subsequent performance: II. Carcass traits at 95 and 145 kilograms live weight. J. Anim. Sci. 68:1929-1935.

Gu, Y., A. P. Schinckel, and T. G. Martin. 1992. Growth, development, and carcass composition in five genotypes of swine. J. Anim. Sci. 70:1719-1729.

Hamilton, D. N., M. Ellis, K. D. Miller, F. K. McKeith, and D. F. Parrett. 2000. The effect of the Halothane and Rendement Napole genes on carcass and meat quality characteristics of pigs. J. Anim. Sci. 78:2862-2867.

Hamilton, D. N., M. Ellis, M. D. Hemann, F. K. McKeith, K. D. Miller, and K. W. Purser. 2002. The impact of longissimus glycolytic potential and short-term feeding of magnesium sulfate heptahydrate prior to slaughter on carcass characteristics and pork quality. J. Anim. Sci. 80:1586-1592.

Hyun, Y. G. E. Bressner, M. Ellis, A. J. Lewis, R. Fischer, E. P. Stanisiewski, and G. F. Hartnell. 2004. Performance of growing-finishing pigs fed diets containing Roundup Ready corn (event nk603), a nontransgenic genetically similar, corn, or conventional corn lines. J. Anim. Sci. 82:571-580.

Latorre, M. A., E. Garcia-Belenguer, and L. Arino. 2008. The effects of sex and slaughter weight on growth performance and carcass traits of pigs intended for dry-cured ham from Teruel (Spain). J. Anim. Sci. 86:1933-1942.

Latorre, M. A., P. Medel, A. Fuentetaja, R. Lázaro, and G. G. Mateos. 2003. Effect of gender, terminal sire line and age at slaughter on performance, carcass characteristics and meat quality of heavy pigs. Anim. Sci. 77:33-45.

Latorre, M. A., R. Lazaro, D. G. Valencia, P. Medel, and G. G. Mateos. 2004. The effects of gender and slaughter weight on the growth performance, carcass traits, and meat quality characteristics of heavy pigs. J. Anim. Sci. 82:526-533.

Leach, L. M., M. Ellis, D. S. Sutton, F. K. McKeith, and E. R. Wilson. 1996. The growth performance, carcass characteristics, and meat quality of halothane carrier and negative pigs. J. Anim. Sci. 74:934-943.

NRC. 1998. Nutrient Requirements of Swine (10^{th} Ed.). National Academy Press. Washington, DC.

Steel, R. G. D. and J. H. Torrie. 1980. Principles and Procedures of Statistics: A Biometrical Approach. 2^{nd} ed. McGraw-Hill Book Co., New York.

Wagner, J. R., A. P. Schinckel, W. Chen, J. C. Forrest, and B. L. Coe. 1999. Analysis of body composition changes of swine during growth and development. J. Anim. Sci. 77:1442-1466.

TABLES

Table 8. Pen mean live weight when pigs the first pigs were removed for harvest and mean number of days between groups sent for harvest.

	Harvest Weight, kg						
Item	113	125	136	147	159	170	181
Pen mean live weight when the first pigs were removed for harvest, kg	99.8	110.1	119.1	130.5	139.3	149.7	159.7
Mean number of days between groups sent for harvest	4.2	4.0	4.4	5.4	6.5	8.0	8.3

Table 9. Least-squares means for the effects of Gender and Harvest Weight on growth performance of pigs.

	Gender				Harvest Weight, kg									
Item	Barrows	Gilts	SEM	*P*-value	113	125	136	147	159	170	181	SEM	*P*-value	Gender × HW *P*-value
Number of pens	56	56	-	-	16	16	16	16	16	16	16	-	-	-
Body weight, kg														
Week 0 (start)	5.8	5.8	0.13	0.21	5.8	5.8	5.8	5.8	5.8	5.8	5.8	0.13	0.29	0.68
End of study[1,2]	145.6^{a}	144.7^{b}	0.48	0.04	114.7^{g}	123.5^{f}	133.9^{e}	144.9^{d}	157.1^{c}	166.3^{b}	175.8^{a}	0.66	<0.001	0.06
Coefficient of variation (within-pen), %														
Week 0 (start)	19.5^{b}	20.0^{a}	0.68	<0.001	19.7	19.8	19.7	19.7	19.7	19.7	19.9	0.69	0.88	0.76
Approximately 2 weeks prior to start of harvest[3]	10.0	10.3	0.24	0.26	11.6^{a}	10.6^{ab}	9.6^{bc}	10.5^{bc}	9.7^{bc}	9.9^{bc}	9.4^{c}	0.40	0.002	0.10
Days to first removal of pigs from pen for harvest[2]	147.0^{b}	151.8^{a}	1.01	<0.001	117.5^{g}	126.9^{f}	136.6^{e}	149.1^{d}	159.6^{c}	171.5^{b}	184.3^{a}	1.28	<0.001	0.14
Overall average daily gain, kg[4]	0.826^{a}	0.802^{b}	0.0055	<0.001	0.810^{bc}	0.823^{ab}	0.831^{a}	0.821^{ab}	0.822^{ab}	0.802^{cd}	0.789^{d}	0.0072	<0.001	0.38
Overall average daily feed intake, kg[4]	2.21^{a}	2.09^{b}	0.010	<0.001	1.92^{f}	2.02^{e}	2.11^{d}	2.16^{c}	2.25^{b}	2.27^{b}	2.32^{a}	0.016	<0.001	0.47
Overall gain:feed[4]	0.376^{b}	0.386^{a}	0.0014	<0.001	0.424^{a}	0.410^{b}	0.395^{c}	0.380^{d}	0.366^{e}	0.353^{f}	0.340^{g}	0.0019	<0.001	0.02
Gender														
Barrows	-	-	-	-	0.423^{ab}	0.401^{c}	0.388^{d}	0.375^{e}	0.359^{f}	0.348^{g}	0.338^{h}	0.0025	-	-
Gilts	-	-	-	-	0.425^{a}	0.418^{b}	0.401^{c}	0.385^{d}	0.373^{e}	0.358^{f}	0.342^{gh}	-	-	-
Carcass average daily gain, kg[5,6]	0.564^{a}	0.546^{b}	0.0036	<0.001	0.539^{d}	0.553^{bc}	0.563^{ab}	0.563^{ab}	0.565^{a}	0.555^{abc}	0.548^{cd}	0.0048	<0.001	0.24
Carcass gain:feed[7]	0.256^{b}	0.263^{a}	0.0009	<0.001	0.282^{a}	0.274^{b}	0.267^{c}	0.261^{d}	0.252^{e}	0.244^{f}	0.236^{g}	0.0013	<0.001	0.02
Gender														
Barrows	-	-	-	-	0.280^{a}	0.269^{bc}	0.263^{d}	0.257^{e}	0.247^{f}	0.242^{g}	0.236^{h}	0.0017	-	-
Gilts	-	-	-	-	0.283^{a}	0.280^{a}	0.272^{b}	0.265^{cd}	0.256^{e}	0.247^{f}	0.237^{h}	-	-	-
Morbidity and mortality, %	5.71	5.00	-	0.29	4.38	5.63	5.00	4.06	5.00	6.56	6.88	-	0.36	0.74

^{a,b,c,d,e,f,g,h} Means within a row or interaction subclass with different superscripts differ ($P \leq 0.05$).

[1]Gender means were not corrected for differences in end of study live weight.

[2]Time at which last pigs in the pen were sent for harvest.

[3]Individual weights were collected on all pens within a treatment group 1 to 2 weeks prior to the first removal of pigs from the heaviest pen within the treatment group.

[4]Performance measured from the start of the study (weaning) to the end of study.

[5]Hot carcass weight was recorded after skin, front and hind feet, and head were removed from carcass.

[6]Carcass average daily gain = overall ADG * carcass yield.

[7]Carcass gain:feed = carcass average daily gain / overall ADFI.

Table 10. Summary of regression equations.

Dependent variable	Independent variables[b]	Dependent variable statistics: Mean	Dependent variable statistics: Standard deviation	Parameter estimates[a]: Intercept	Parameter estimates[a]: Linear	Parameter estimates[a]: Quadratic	R^2	RSD[c]
Gender								
Barrows								
Overall average daily gain, kg	End of study live weight, kg	0.83	0.028	-	NS	NS	-	-
Overall average daily feed intake, kg	End of study live weight, kg	2.22	0.151	1.25	0.00664	NS	0.85	0.059
Overall gain:feed, kg:kg	End of study live weight, kg	0.375	0.0287	0.567	-0.00131	NS	0.93	0.0078
Carcass average daily gain, kg[d]	End of study live weight, kg	0.56	0.020	-	NS	NS	-	-
Carcass gain:feed, kg:kg[e]	End of study live weight, kg	0.255	0.0154	0.357	-0.00069	NS	0.91	0.0046
Ultrasound measurements (10^{th} rib)						NS		
Backfat depth, mm	End of study live weight, kg	28.3	4.08	2.0	0.1809	NS	0.90	1.32
Longissimus muscle area, sq. cm	End of study live weight, kg	49.5	4.22	21.2	0.1940	NS	0.94	1.00
Longissimus muscle depth, cm	End of study live weight, kg	5.62	0.244	4.07	0.01066	NS	0.85	0.095
Predicted carcass lean content (lipid-free), %[f]	End of study live weight, kg	60.4	6.90	72.0	-0.1083	NS	0.94	0.57
Carcass yield, %[g]	Harvest live weight, kg	68.2	1.20	60.8	0.0508	NS	0.84	0.48
Gilts								
Overall average daily gain, kg	End of study live weight, kg	0.80	0.028	0.85	-0.00036	NS	0.33	0.023
Overall average daily feed intake, kg	End of study live weight, kg	2.09	0.142	1.19	0.00622	NS	0.87	0.051
Overall gain:feed, kg:kg	End of study live weight, kg	0.386	0.0294	0.578	-0.00133	NS	0.94	0.0074
Carcass average daily gain, kg[d]	End of study live weight, kg	0.55	0.020	-	NS	NS	-	-
Carcass gain:feed, kg:kg[e]	End of study live weight, kg	0.263	0.0165	0.369	-0.00074	NS	0.89	0.0055
Ultrasound measurements (10^{th} rib)								
Backfat depth, mm	End of study live weight, kg	24.8	4.51	-4.5	0.2022	NS	0.91	1.33
Longissimus muscle area, sq. cm	End of study live weight, kg	51.1	4.60	-13.4	0.6951	-0.00169	0.96	0.90
Longissimus muscle depth, cm	End of study live weight, kg	5.74	0.282	0.04	0.06789	-0.000190	0.92	0.079
Predicted carcass lean content (lipid-free), %[f]	End of study live weight, kg	61.8	6.84	76.3	-0.1265	NS	0.97	0.49
Carcass yield, %[g]	Harvest live weight, kg	68.1	1.06	62.0	0.0419	NS	0.73	0.54

[a]"NS" = not significant ($P > 0.05$).
[b]End of study live weight is the actual mean live weight of each pen at the end of test.
[c]Residual standard deviation.
[d]Carcass average daily gain = overall ADG * carcass yield.
[e]Carcass gain:feed = carcass ADG / overall ADFI.
[f]Predicted carcass lean content, % = [8.9 + 0.347 * BW (kg) – 0.379 * 10^{th} rib backfat (mm) + 0.269 * *Longissimus* muscle area (cm^2)] / hot carcass weight (without skin and feet) * 100 [Schinckel, personal communication; data used to develop equation reported in Schinckel et al., 2001; JAS].
[g]Hot carcass weight was recorded after skin, front and hind feet, and head were removed from carcass.

Table 11. Least-squares means for the effects of Gender and Harvest Weight on live animal ultrasound measurements and carcass characteristics of pigs.

	Gender				Harvest Weight, kg									
Item	Barrows	Gilts	SEM	*P*-value	113	125	136	147	159	170	181	SEM	*P*-value	Gender x HW *P*-value
Number of pens	56	56	-	-	16	16	16	16	16	16	16	-	-	-
Live animal ultrasound measurements (10^{th} rib)														
End of study live weight, kg[1]	145.6^{a}	144.7^{b}	0.48	0.04	114.7^{g}	123.5^{f}	133.9^{e}	144.9^{d}	157.1^{c}	166.3^{b}	175.8^{a}	0.66	<0.001	0.06
Backfat depth, mm	28.3^{a}	24.8^{b}	0.21	<0.001	21.2^{g}	22.7^{f}	23.9^{e}	25.6^{d}	29.1^{c}	30.5^{b}	32.8^{a}	0.37	<0.001	0.23
Longissimus muscle area, sq. cm	49.5^{b}	51.1^{a}	0.13	<0.001	43.3^{g}	45.8^{f}	48.6^{e}	51.2^{d}	52.9^{c}	54.3^{b}	55.9^{a}	0.24	<0.001	0.14
Longissimus muscle depth, cm	5.62^{b}	5.74^{a}	0.012	<0.001	5.26^{f}	5.41^{e}	5.57^{d}	5.78^{c}	5.88^{b}	5.92^{ab}	5.94^{a}	0.022	<0.001	0.08
Predicted carcass lean weight (lipid-free), kg[2]	60.4^{b}	61.8^{a}	0.21	<0.001	50.9^{g}	54.0^{f}	57.8^{e}	61.6^{d}	64.9^{c}	67.9^{b}	70.7^{a}	0.27	<0.001	0.06
Predicted carcass lean content (lipid-free), %[3]	61.1^{b}	62.9^{a}	0.11	<0.001	66.6^{a}	65.2^{b}	63.7^{c}	61.9^{d}	60.2^{e}	58.9^{f}	57.6^{g}	0.21	<0.001	0.16
Carcass characteristics														
Harvest live weight, kg[1]	145.7	145.2	0.49	0.20	115.0^{g}	123.4^{f}	134.0^{e}	145.2^{d}	157.0^{c}	166.7^{b}	177.0^{a}	0.67	<0.001	0.05
Gender														
Barrows	-	-	-	-	116.4^{h}	123.8^{g}	133.8^{f}	144.3^{e}	157.0^{d}	166.8^{c}	178.1^{a}	0.86	-	-
Gilts	-	-	-	-	113.7^{i}	123.0^{g}	134.3^{f}	146.2^{e}	157.0^{d}	166.5^{c}	175.8^{b}	-	-	-
Hot carcass weight, kg[4]	99.7^{a}	99.0^{b}	0.31	0.03	76.5^{g}	82.8^{f}	90.8^{e}	99.5^{d}	107.9^{c}	115.2^{b}	122.9^{a}	0.45	<0.001	0.01
Gender														
Barrows	-	-	-	-	77.3^{i}	83.2^{h}	90.6^{g}	98.7^{f}	108.0^{d}	115.8^{c}	124.1^{a}	0.59	-	-
Gilts	-	-	-	-	75.6^{j}	82.4^{h}	90.9^{g}	100.3^{e}	107.8^{d}	114.7^{c}	121.6^{b}	-	-	-
Carcass yield, %[4]	68.2	68.1	0.07	0.08	66.5^{e}	67.1^{d}	67.7^{c}	68.6^{b}	68.7^{b}	69.1^{a}	69.4^{a}	0.12	<0.001	0.19

[a,b,c,d,e,f,g,h,i,j] Means within a row or interaction subclass with different superscripts differ ($P \leq 0.05$).

[1]Gender means were not corrected for differences in end of study live weight or harvest live weight.

[2]Predicted carcass lean weight, kg = 8.9 + 0.347*BW (kg) – 0.379*10th rib backfat (mm) + 0.269**Longissimus* muscle area (cm^2) [Schinckel, personal communication; data used to develop equation reported in Schinckel et al., 2001; JAS].

[3]Predicted carcass lean content, % = Predicted carcass lean weight / hot carcass weight * 100.

[4]Hot carcass weight was recorded after skin, front and hind feet, and head were removed from carcass.

FIGURES

Figure 8. Regression of overall average daily feed intake against the mean live weight of each pen at the end of test.

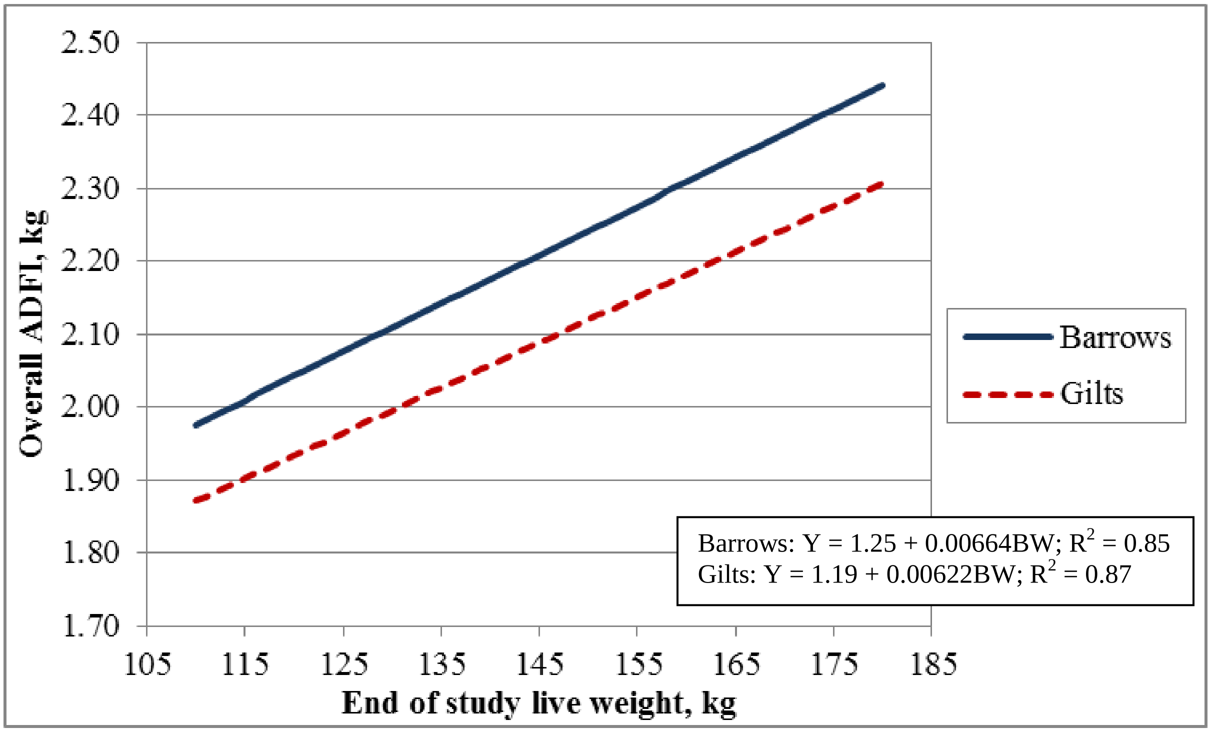


Figure 9. Regression of overall gain:feed against the mean live weight of each pen at the end of test.

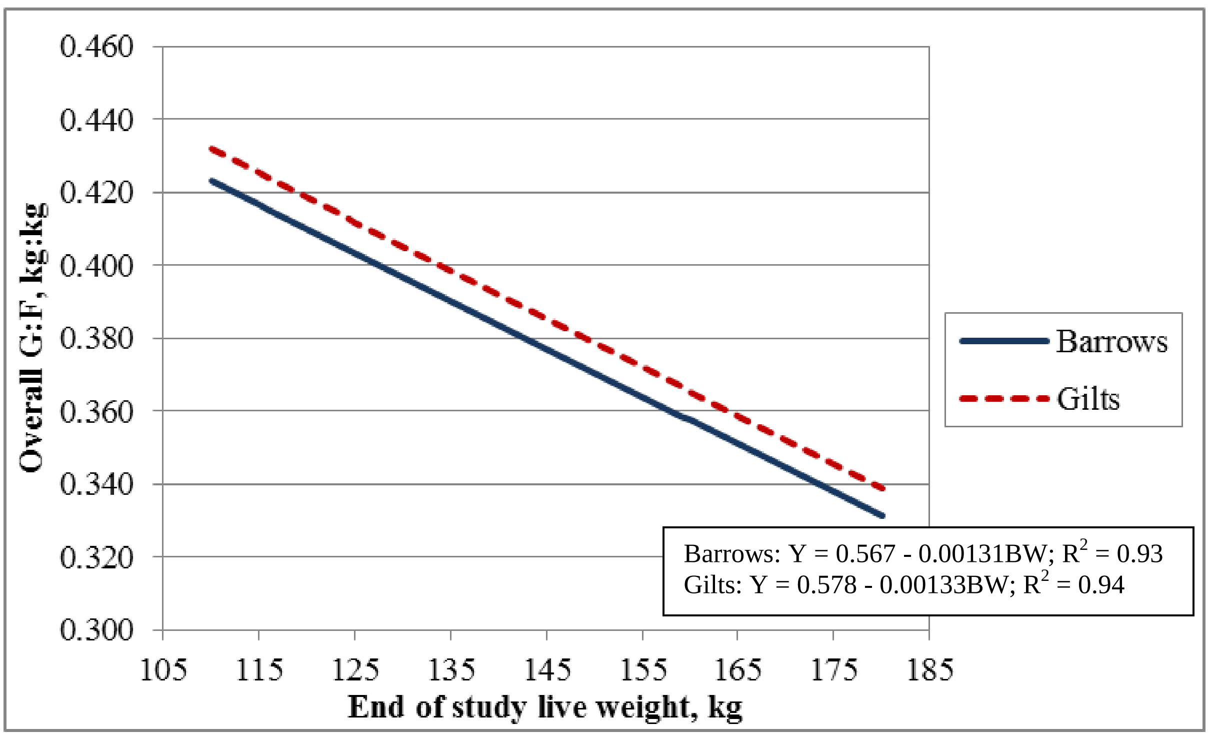


Figure 10. Regression of overall carcass gain:feed against the mean live weight of each pen at the end of test.

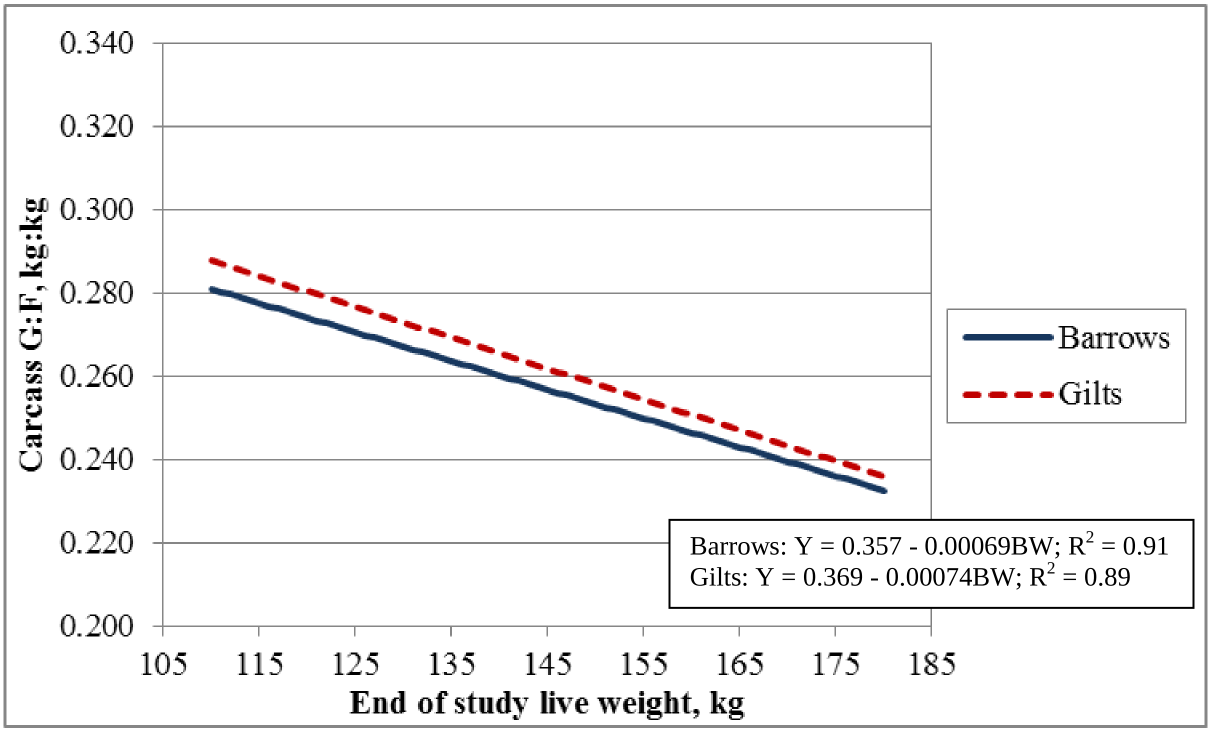


Figure 11. Regression of backfat depth (10th rib) measured ultrasonically against the mean live weight of each pen at the end of test.

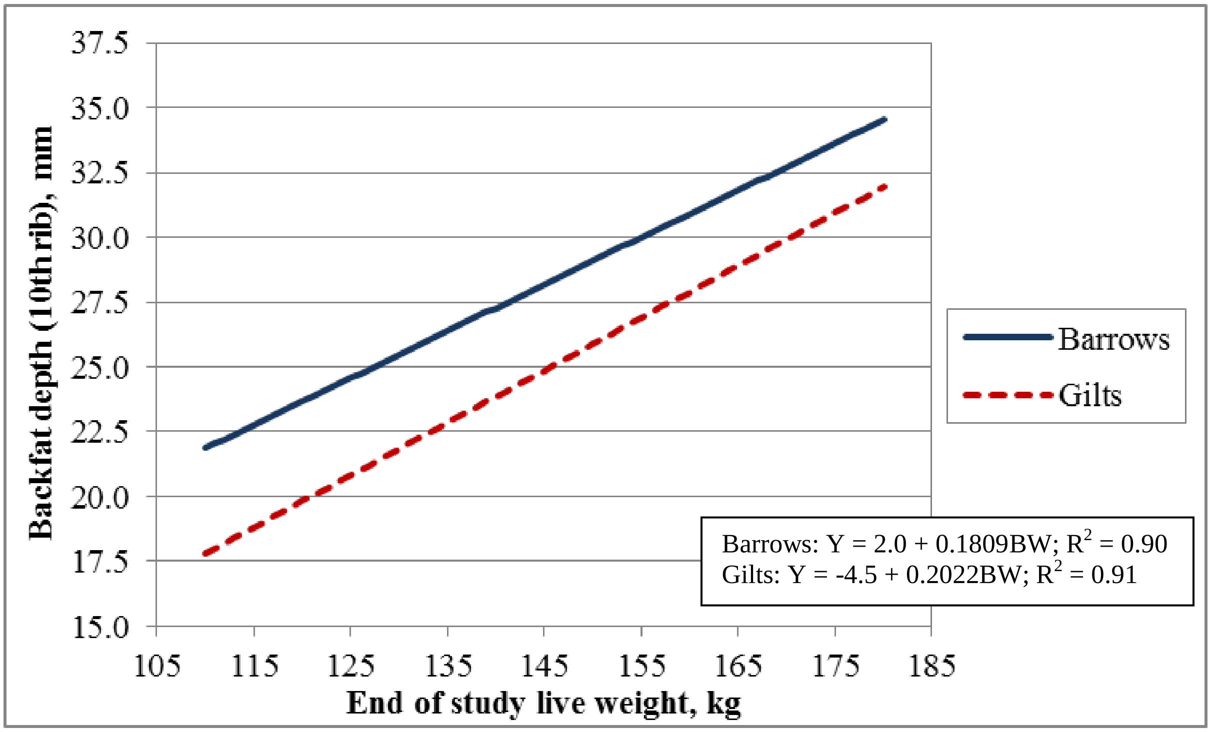


Figure 12. Regression of *Longissimus* muscle area (10th rib) measured ultrasonically against the mean live weight of each pen at the end of test.

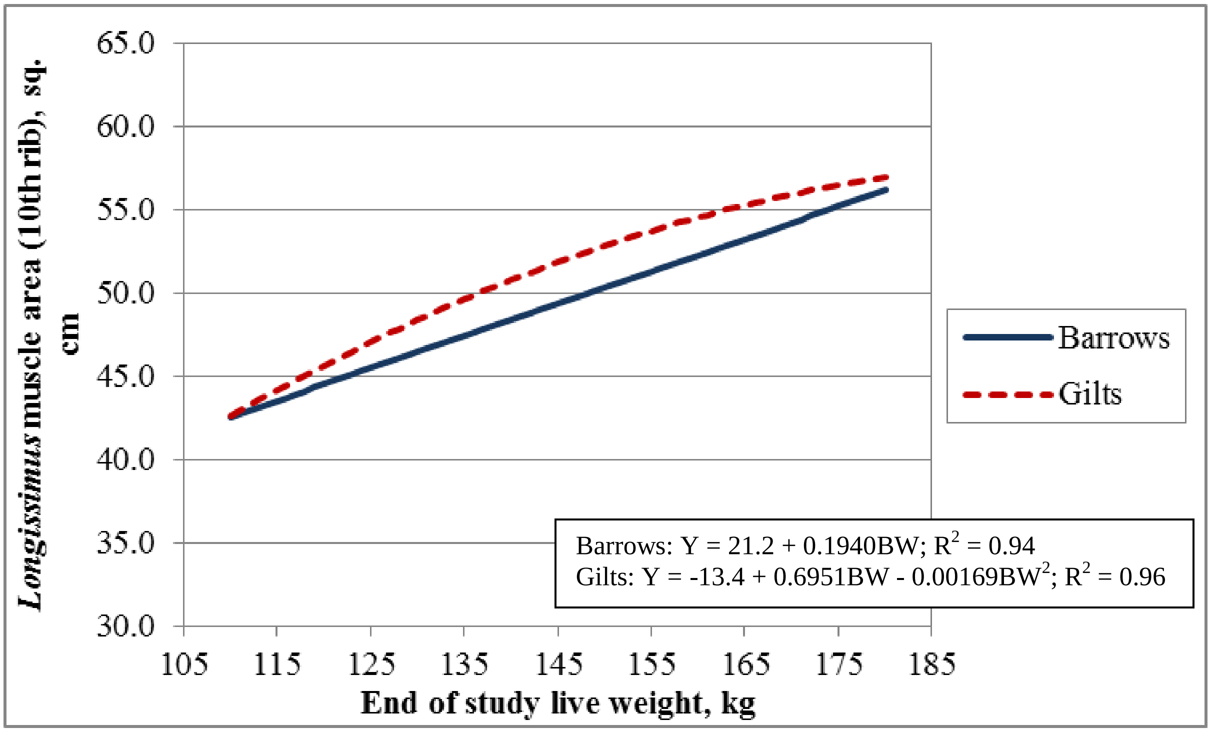


Figure 13. Regression of *Longissimus* muscle depth (10th rib) measured ultrasonically against the mean live weight of each pen at the end of test.

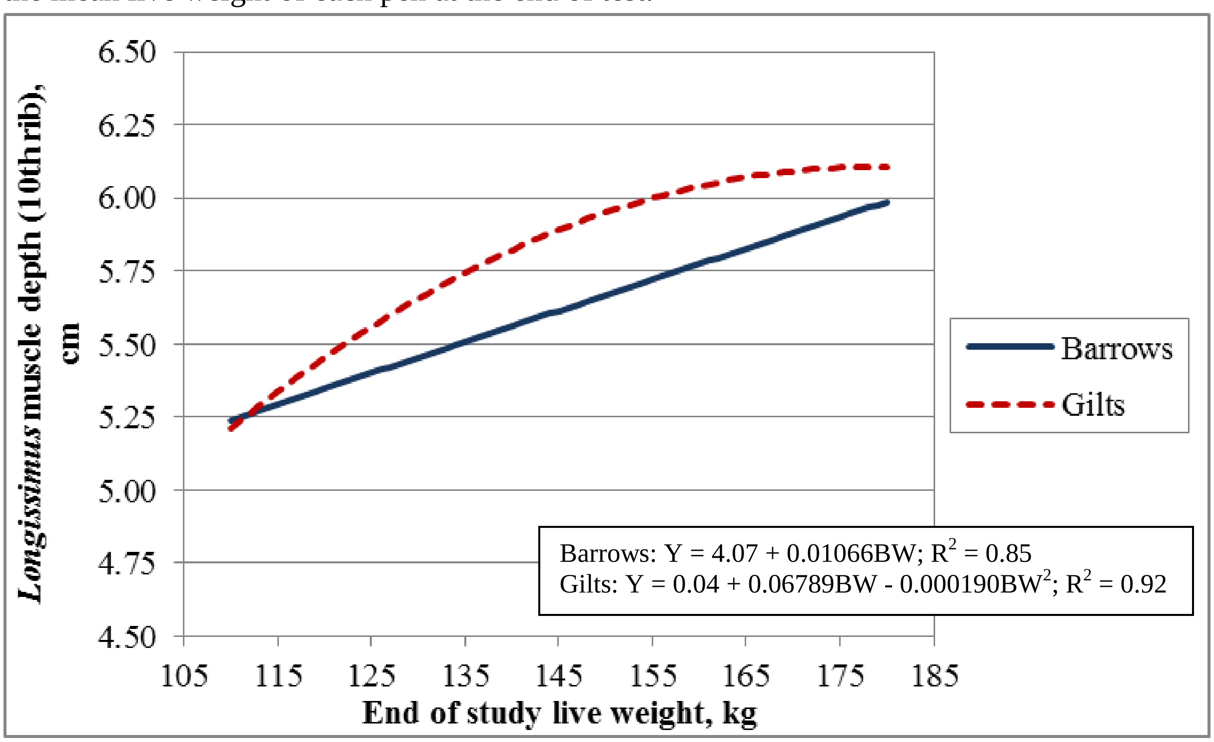


Figure 14. Regression of predicted carcass lean content (lipid-free) against the mean live weight of each pen at the end of test.

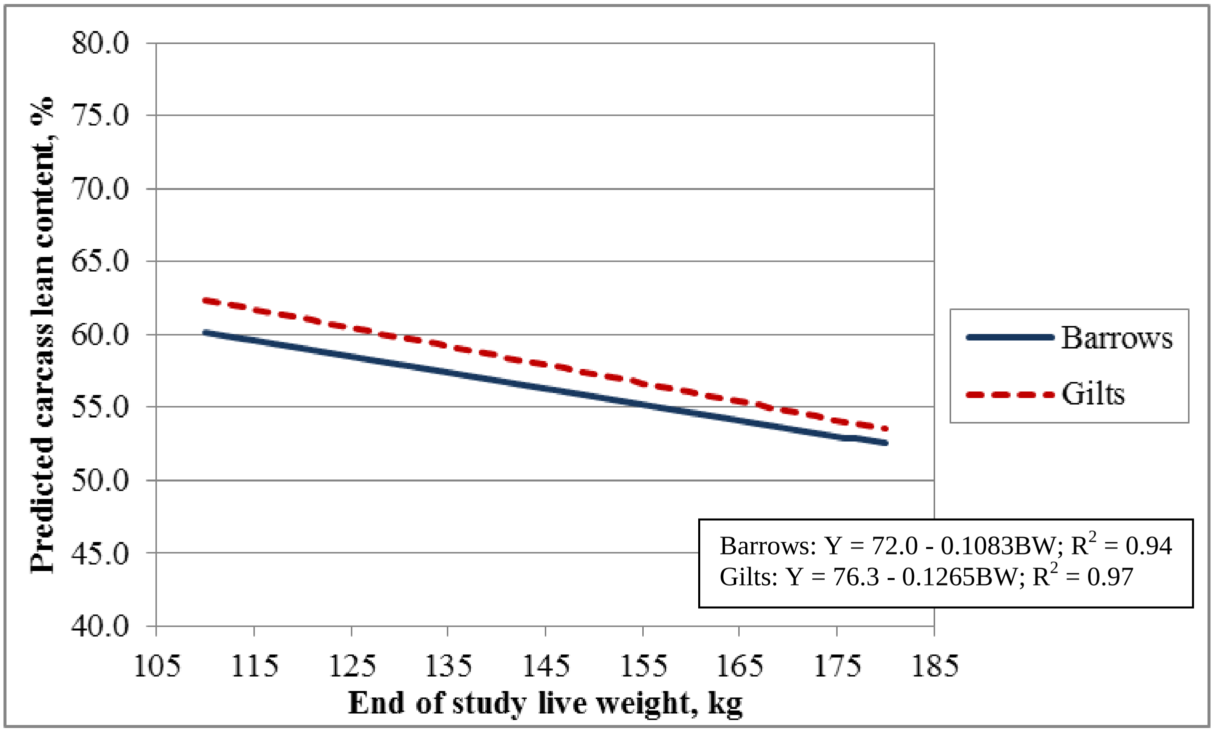
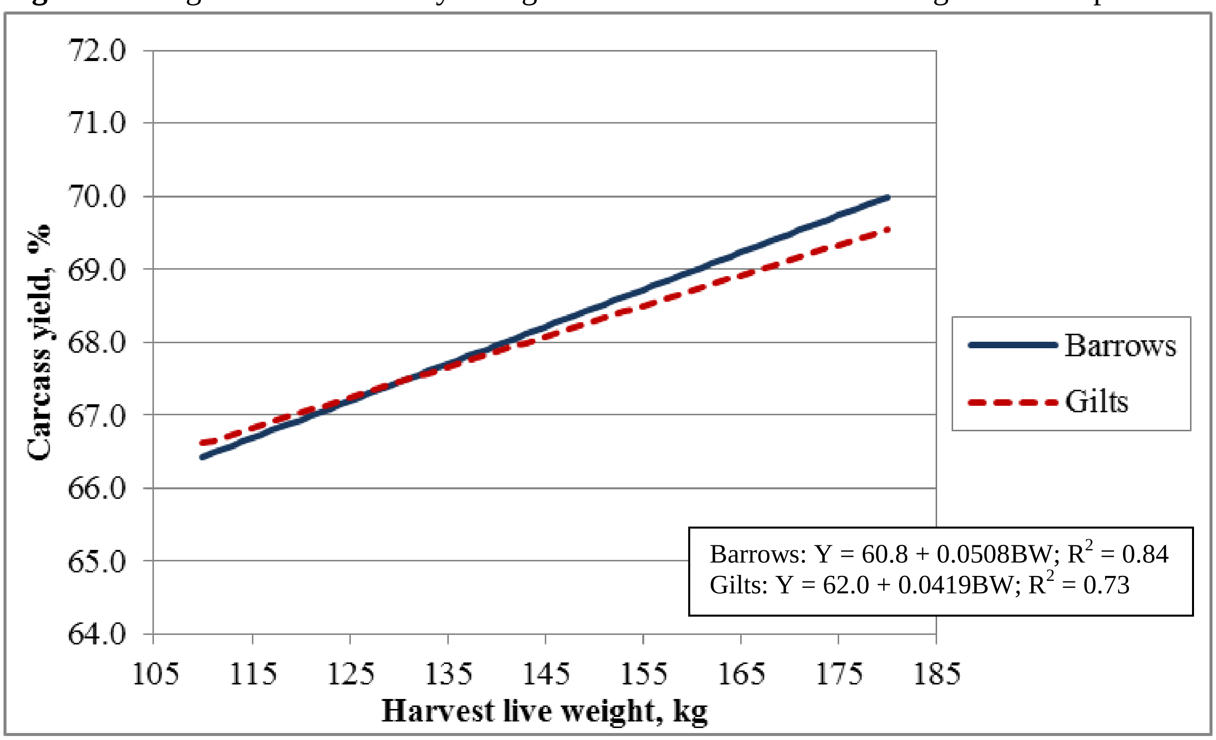


Figure 15. Regression of carcass yield against the mean harvest live weight for each pen.



CHAPTER 4: DEVELOPMENT OF INDIVIDUAL PIG GROWTH CURVES FOR BARROWS AND GILTS REARED IN A COMMERCIAL WEAN-TO-FINISH FACILITY.

ABSTRACT

The objectives of this study were to: 1) Develop relationships between live weight and instantaneous average daily gain for barrows and gilts using data sets based on both the pen mean and also individual pig data, 2) Determine the impact of birth weight on the relationship between live weight and instantaneous average daily gain, 3) Develop relationships between live weight and within-pen variation in live weight, and 4) Determine the extent to which the within-pen ranking of individual pigs for live weight changes during the growth period. The study was conducted as a RCBD with a single treatment, namely gender (barrows and gilts). The study was carried out using 6 replicates with 12 pens (1,882 pigs) from weaning to week 10 post-weaning. At week 10 post-weaning, 3 replicates (3 pens of barrows and 3 pens of gilts) were removed from the study leaving 3 replicates for a total of 880 pigs on test (excluding mortalities or morbid pigs removed prior to week 10 post-weaning). Each of the remaining pens was split into 2 groups with similar mean live weight and variation in live weight, resulting in 12 pens from week 10 post-weaning to the end of test, which occurred at a pen mean live weight of 135.2 ± 0.76 kg. Pigs had ad libitum access to food and water throughout the study. A floor space of approximately 0.28 and 0.59 m^2/pig was provided from weaning to week 10 post-weaning and week 10 post-weaning to the end of test, respectively. Instantaneous ADG increased as live weight increased up to approximately 70 to 80 kg, and then decreased, and was generally higher for barrows than gilts across the majority of the weight range evaluated. Birth weight had a significant ($P \leq 0.05$) impact on the intercept and linear and quadratic coefficients for live weight, with higher birth weight pigs having a higher instantaneous ADG curve across the entire

weight range evaluated. However, these results should be interpreted with caution as instantaneous ADG curves that were developed using individual pig data, including those that were developed for pigs with different birth weights, were biased because not all individual pigs were evaluated over the same weight range. Within-pen standard deviation increased quadratically ($P \leq 0.05$) and within-pen coefficient of variation decreased linearly ($P \leq 0.05$) as live weight increased from weaning to week 10 post-weaning and from week 10 post-weaning to the end of test for both barrows and gilts. Correlations between the within-pen live weight rank at birth and weaning and within-pen live weight rank in subsequent periods were between 0.5 and 0.6 ($P \leq 0.05$). The percentage of pigs in the same live weight quartile at week 22 post-weaning as they were in at birth, weaning, and week 10 post-weaning was 39.0, 40.7, and 57.8%, respectively. The results of this study suggest that when pens are taken off test at a mean live weight, rather than taking individual pigs off test, the use of pen means in the regression analysis is likely to provide a more accurate estimate of the mean growth rate of the population than using individual pig data. Additionally, these results suggest that standard deviation for live weight increases as live weight increases and that gender and birth weight both impact the growth curve of individual pigs. Lastly, interim weights were shown to be relatively poor predictors of subsequent growth of individual pigs within a pen.

INTRODUCTION

In commercial production, pigs are sold on an individual basis. For this reason, the growth of individual pigs within a population must be considered. A number of studies have developed growth curves for individual pigs that were reared under controlled research conditions and showed that the variation in growth and live weight within a population of pigs increases as pigs increase in weight (Schinckel et al., 2003; Strathe et al., 2010). However, growth curves for individual pigs in large groups in a commercial environment have not been established. Studies have also shown that a portion of the variation in growth rate between pigs within a population can be attributed to birth weight, as heavier pigs at birth will generally grow faster than lighter pigs heavier in subsequent growth periods (Wolter et al., 2002; Rehfeldt and Kuhn, 2006). Understanding the variation in growth within a pen of pigs will be of value during the marketing process that occurs in commercial practice in which individual pigs are removed from pens and sent for harvest. Other opportunities may also exist in which slower growing or faster growing pigs may be managed differently to improve the production of the entire group. Therefore, the objectives of this study were to: 1) Develop relationships between live weight and instantaneous average daily gain for barrows and gilts using data sets based on both the pen mean and also individual pig data, 2) Determine the impact of birth weight on the relationship between live weight and instantaneous average daily gain, 3) Develop relationships between live weight and within-pen variation in live weight, and 4) Determine the extent to which the within-pen ranking of individual pigs for live weight changes during the growth period (i.e., from birth to week 22 post-weaning).

MATERIALS AND METHODS

The study was conducted in a standard wean-to-finish facility at the The Maschhoffs' Mach 9 Research Center located near Beardstown, IL. The experimental protocol was approved by the University of Illinois Institutional Animal Care and Use Committee (IACUC #11194).

Experimental Design and Treatments. The study was carried out as a randomized complete block design with a single treatment, namely gender (barrows and gilts). Location of the pens within a room was the blocking factor. There were a total of 12 pens (6 replicates) from weaning to week 10 post-weaning. At week 10 post-weaning, six pens (3 replicates) were taken off test, and each of the remaining six pens (3 replicates) was split into 2 equal groups and one group was moved to one of the pens that were previously occupied by the pens that had been taken of test.

Animals and Allotment. Pigs were the progeny of PIC 359 sires mated to PIC C29 dams (PIC, Hendersonville, KY). At birth, piglets were weighed individually and tagged with a unique identification number and their litter of origin was recorded. Cross-fostering of piglets between litters occurred after the piglets were weighed and this typically occurred within a room. On each weaning day, all of the sows and piglets in a farrowing room were weaned, excluding piglets that were below 2.5 kg body weight. On the day of weaning, pigs were weighed individually and re-tagged. A replicate consisted of 1 pen of barrows and 1 pen of gilts and all pigs within a litter were allotted to the same replicate. Pigs were assigned to replicates such that, within a replicate, the pen of barrows and pen of gilts had similar group size (~153), mean birth and weaning weight, and within-pen variation in birth and weaning weight. From weaning to week 10 post-weaning, a total of 1,882 animals were used and these were housed in 10 pens of ~153 pigs and 2 pens of ~175 pigs. At week 10 post-weaning, 3 replicates (3 pens of barrows and 3 pens of gilts) were removed from the study leaving 3 replicates with a total of 880 pigs on test (excluding mortalities or morbid pigs removed prior to week 10 post-weaning). The replicates that remained on the study were selected because they all had the same day of start on test and initial group size (~153 pigs) at the start of test. For these 3 remaining replicates, each of the 6 pens was split into 2 equal group sizes of ~73 pigs with similar mean live weight and variation in live weight and one of the groups was moved to a pen in a different room of the building. All pigs from the same litter remained in the same room. Pens of pigs from these 3 replicates were taken off test when the mean live weight of the pen was 135.2 ± 0.76 kg.

Housing and Diets. Pigs were housed in a wean-to-finish building that had fully slatted concrete flooring and was tunnel ventilated. Pen divisions consisted of gates with horizontal steel rods and pen dimensions (length x width) were 14.38 x 3.05 m (14.38 x 3.45 m for the 2 pens of ~175 pigs), which provided a floor space of approximately 0.28 and 0.59 m^2/pig from weaning to week 10 post-weaning and week 10 post-weaning to the end of test, respectively. Pen size was not adjusted in the event of a mortality or removal of a morbid pig during the study. Air temperature was maintained using thermostatically controlled heaters and fan ventilation. The thermostat was maintained at 27° C for the first week post-weaning and lowered in subsequent weeks until it reached 18° C where it was maintained for the duration of the study. During the first 14 days post-weaning, supplemental heat was provided by one heat reflective heat lamp (125 W) per pen suspended 75 cm above the floor. Under hot conditions when the ambient room temperature reached 29.4° C, water sprinklers were used in an attempt to cool the pigs.

Each pen was equipped with two 4-hole wet/dry box feeders (Feed Ease Wet/Dry Feeder, A. J. O'Mara Group, Lyons, NE) with access to only one side of each feeder which provided

284.5 cm of feeder trough space (approximately 1.8 and 3.9 cm/pig from weaning to week 10 post-weaning and week 10 post-weaning to end of test, respectively). Two additional water cups were available in each pen. Pigs had ad libitum access to feed and water. An 8-phase dietary program was used and diets were formulated to meet or exceed NRC (1998) recommendations for nutrient requirements of pigs across the range of weights evaluated.

Growth Measurements. Pigs were weighed individually at birth and every 2 weeks from weaning to the end of test. Pigs experiencing health problems or injuries that did not respond to treatment were removed from the study and the date of, pig weight at, and reason for removal were recorded; the weight of pigs removed was included in the calculation of growth rate.

Statistical Analysis. All data were tested for normality using the PROC UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC). Data meeting the criteria for normality were analyzed using the PROC MIXED procedure of SAS as a randomized complete block design with pen as the experimental unit. The model used included the fixed effect of gender and the random effect of block. Least-squares means were compared using the PDIFF and STDERR options of SAS with means considered different with $P \leq 0.05$.

Regression analysis was conducted using the PROC MIXED procedure of SAS. Using both pen means and individual pig data, polynomial equations were developed between period mean live weight (calculated as the mean of the live weights at the start and end of a 2-week weigh period) and instantaneous ADG. The model using pen mean data included the random effect of block and the model using individual pig data included the random effects of block and pig nested within block. A multi-variable regression model was developed for the prediction of instantaneous ADG that included the fixed effects of gender, birth weight, and the linear, quadratic, and cubic coefficients for period mean live weight and all interactions, and the random effect of block. Polynomial equations were also developed between live weight and within-pen standard deviation and coefficient of variation in live weight. For all equations, coefficients or interaction terms that were found to be not significant ($P > 0.05$) using the log-likelihood test were removed. The coefficient of determination (R^2) and residual standard deviation (RSD) were calculated for each regression equation.

Within-pen live weight rank was assigned to each pig by sorting all pigs within a pen by live weight from the lightest to heaviest pig and assigning a numerical rank. Correlation coefficients were calculated between the live weight rank at birth, weaning, week 10 post-weaning, and week 22 post-weaning. Also, the change in live weight rank within a pen was analyzed by categorizing pigs into 4 live weight quartiles (quartile 1 = lightest 25%, quartile 2 = next lightest 25%, quartile 3 = next lightest 25%, quartile 4 = heaviest 25%) at birth, weaning, week 10 post-weaning, and week 22 post-weaning. The percentage of pigs that were in the same live weight quartile at the following times was calculated:

1. Birth and subsequent time points (weaning and week 10 and 22 post-weaning).
2. Weaning and subsequent time points (week 10 and 22 post-weaning).
3. Week 10 and 22 post-weaning.

RESULTS AND DISCUSSION

Growth performance data for all 6 replicates from birth to week 10 post-weaning are presented in Table 12. Barrows had a higher ($P \leq 0.05$) live weight at birth; however, this difference was numerically small (0.04 kg; 2.8%; Table 12). Within-pen coefficient of variation (CV) was higher ($P \leq 0.05$) for barrows compared to gilts at weaning and week 10 post-weaning (Table 12). It is not clear why there was a difference in live weight and within-pen CV between the genders during this period. There was no difference ($P > 0.05$) between genders in either live weights or ADG from weaning to week 10 post-weaning (Table 12).

Growth performance data from birth to the end of test for the 3 replicates that remained on test after week 10 post-weaning are presented in Table 13. Overall ADG from weaning to the end of test was 5.3% higher ($P \leq 0.05$) for barrows than gilts (Table 13). Within-pen CV at the end of test and morbidity and mortality was similar ($P > 0.05$) between genders (Table 13). Pigs experienced a respiratory infection during the study, which resulted in relatively high levels of morbidity and mortality (Table 13). In general, barrows and gilts performed similarly to previous studies in which both genders were evaluated (Cisneros et al., 1996; Latorre et al., 2004).

Regression Analysis. Regression equations between period mean live weight and instantaneous ADG from weaning to the end of test developed for barrows and gilts using both individual pig data and pen means are presented in Table 14 and illustrated graphically in Figure 16. When data from individual pigs was used, the linear, quadratic, and cubic terms for period mean live weight were all significant ($P \leq 0.05$), whereas, when pen means were used, only the linear and quadratic terms were significant. Instantaneous ADG increased as live weight increased up to approximately 70 and 80 kg for the individual pig and pen means data sets, respectively, and then decreased, and for both data sets, was generally higher for barrows than gilts across the majority of the weight range evaluated (Figure 16). These results are very similar to those of Hamilton et al. (2000) in which instantaneous ADG was regressed against live weight for barrows and gilts. The difference in results when individual pig data was used compared to pen means is likely, in part, due to the large difference in the number of observations used to develop the equations. However, there are other reasons to expect a different shaped growth curve for the different data sets in this study. A major issue with using data from individual pigs within a pen to develop equations between live weight and instantaneous ADG is that, when the pen is taken off test at a fixed pen mean live weight, the growth curves are biased by the fact that not all pigs were represented across the same weight range. The lighter, slower growing pigs were lighter at the end of test and, therefore, the only data points above the target weight were those from the heavier, faster-growing pigs. This would not be an issue if the growth of pigs was linear; however, this and other studies have shown that the growth of pigs increases to a maximum and then decreases thereafter (Hamilton et al., 2003; Schinckel et al., 2009). Thus, it is critical to have sufficient data points above and below the live weight at which maximum growth rate occurs for each pig when developing growth curves using individual pig data. Therefore when pens are taken off test at a mean live weight, rather than taking individual pigs off test, the use of pen means in the regression analysis will probably provide a more accurate estimate of the mean growth rate of the population than that based on individual pig data.

The results of including both gender and birth weight as additional parameters in the polynomial regression equation between period mean live weight and instantaneous ADG are presented in Table 15 and illustrated graphically in Figure 17. In the reduced model, the linear, quadratic, and cubic coefficients for period mean live weight were all significant (Table 15; $P \leq 0.05$). In addition, the intercept and linear and quadratic coefficients for period mean live weight were all different ($P \leq 0.05$) between genders and also impacted by birth weight ($P \leq 0.05$). This suggests that both gender and birth weight impact the shape of the instantaneous ADG curve. In general, the instantaneous ADG curve was higher across majority of the weight range for pigs with heavier birth weights (Figure 17). A number of studies have shown that light birth weight pigs have reduced post-natal growth rates compared to heavy birth weight pigs (Puls, 2009;

Beauleiu et al., 2010). Peterson et al. (2008) evaluated 3 birth weight categories [Heavy (mean of 1.9 kg), Medium (mean of 1.5 kg), and Light (mean of 1.2 kg)] and reported different shaped curves between the 3 categories when instantaneous ADG was regressed against live weight, with pigs from the heavy birth weight category having the highest instantaneous ADG curve and pigs from the light birth weight category having the lowest curve. In the current study, entire pens of pigs were taken off test when they reached a mean live weight of approximately 135 kg. Therefore, the fastest growing pigs (i.e., the heavy birth weight pigs) would be heavier at the end of test than the slower growing pigs (i.e., the light birth weight pigs). As a result, the instantaneous ADG curves for different birth weights are biased by the range of weights evaluated. The obvious solution to this issue is to take every pig within a pen to the same live weight. This, however, would confound the effect of birth weight with either pig removal, if the heaviest pigs were removed from the pen when they reached the target fixed weight, or floor space (relative to live weight), if the heaviest pigs remained in the pen until the lightest pig reached the target fixed weight. To avoid confounding with floor space when allowing each pig within the pen to reach the target live weight, pigs could be housed at a floor space above that which would restrict growth and this should be considered in future studies.

Regression equations between live weight and within-pen standard deviation and coefficient of variation in live weight are presented for barrows and gilts in Table 14 and illustrated graphically in Figures 18 to 21. Within-pen standard deviation increased quadratically ($P \leq 0.05$) and within-pen coefficient of variation in live weight decreased linearly ($P \leq 0.05$) as live weight increased from weaning to week 10 post-weaning and from week 10 post-weaning to the end of test for both barrows and gilts (Table 14). This agrees with previous studies that monitored individual pig growth which generally reported an increase in live weight standard deviation and a decrease in coefficient of variation as live weight increased (Schinckel et al., 2003; Schinckel et al., 2009). Both within-pen standard deviation and coefficient of variation in live weight were generally predicted to be numerically higher for gilts than barrows across the majority of the weight range evaluated in both the nursery and grow-finish periods until the end of the study, at which point there appeared to be no difference (Figures 18 to 21). Other studies have generally not found a difference in within-pen standard deviation between genders; however, additional research is required to clearly establish the effect of gender on within-pen variation in live weight.

Live Weight Rank. Correlation coefficients between the live weight rank at birth, weaning, and week 10 and 22 post-weaning are presented in Table 16. Live weight rank at birth, weaning, and week 10 and 22 post-weaning were all correlated ($P \leq 0.05$) with one another. This suggests that pigs that are heavier at birth and weaning will generally remain heavier during subsequent periods; however, the correlations were relatively weak (correlation coefficients between 0.5 and 0.6; Table 16). A number of studies have reported that heavier pigs at birth (Schinckel et al., 2007; Puls, 2009; Beauleiu et al., 2010) and weaning (Klindt, 2003; Schinckel et al., 2007) had higher post-weaning growth rates than their lighter counterparts. However, pigs that are heavier at weaning are also likely to be heavier at birth. Therefore, the effects of weaning weight on subsequent growth performance could be partly due to differences in birth weight. Studies that have evaluated weaning weight effects separately from the effects of birth weight by either changing the number of pigs nursed per litter (Peterson et al., 2008) or providing supplemental nutrition to piglets (Wolter et al., 2002; Klindt, 2003) have shown that weaning weight had little impact on subsequent growth performance. The highest correlation amongst the live weight rank data was between the within-pen rankings in live weight at week 10 and 22 post-weaning (correlation of 0.82; Table 16).

The number and percentage of pigs that remained in the same quartile at various times is presented in Table 17. The percentage of pigs in the same live weight quartile at week 22 post-weaning as they were in at birth, weaning, and week 10 post-weaning was 39.0, 40.7, and 57.8%, respectively. These results support those of the live weight rank analysis and suggest that pigs change live weight rank less often when they reach heavier weights. Nevertheless, almost half of the pigs changed quartiles from week 10 to week 22 post-weaning, which reemphasizes that a significant amount of variation in growth rates between pigs exists and that interim weights are relatively poor predictors of subsequent growth. Furthermore, the number of pigs in the same live weight quartile at week 22 post-weaning as they were in at birth, weaning, and week 10 post-weaning was generally greater for the lightest and heaviest quartiles (quartiles 1 and 4, respectively) than for the intermediate quartiles (quartiles 2 and 3). Pigs in the intermediate live weight quartiles would inherently have less variation in weight and, therefore, would require less of a change in live weight to move into another quartile.

CONCLUSIONS

The results of this study suggest that individual pig growth within a pen is extremely variable. These results also suggest that standard deviation for live weight increases as live weight increases and that gender and birth weight both impact the growth curve of individual pigs. Additionally, interim weights were shown to be relatively poor predictors of subsequent growth of individual pigs within a pen.

LITERATURE CITED

Beauleiu, A. D., J. L. Aalhus, N. H, Williams, and J. F. Patience. 2010. Impact of piglet birth weight, birth order, and litter size on subsequent growth performance, carcass quality, muscle composition, and eating quality of pork. J. Anim. Sci. 88:2767-2778.

Cisneros F., M. Ellis, F. K. McKeith, J. McCaw, and R. L. Fernando. 1996. Influence of slaughter weight on growth and carcass characteristic, commercial cutting and curing yields, and meat quality of barrows and gilts from two genotypes. J. Anim. Sci. 74:925-933.

Hamilton, D. N., M. Ellis, B. F. Wolter, A. P. Schinckel, and E. R. Wilson. 2003. The growth performance of the progeny of two swine sire lines reared under different floor space allowances. J. Anim. Sci. 81:1126-1135.

Hamilton, D. N., M. Ellis, K. D. Miller, F. K. McKeith, and D. F. Parrett. 2000. The effect of the Halothane and Rendement Napole genes on carcass and meat quality characteristics of pigs. J. Anim. Sci. 78:2862-2867.

Klindt, J. 2003. Influence of litter size and creep feeding on pre-weaning gain and influence of pre-weaning growth on growth to slaughter in barrows. J. Anim. Sci. 83:2434-2439.

Latorre, M. A., R. Lazaro, D. G. Valencia, P. Medel, and G. G. Mateos. 2004. The effects of gender and slaughter weight on the growth performance, carcass traits, and meat quality characteristics of heavy pigs. J. Anim. Sci. 82:526-533.

NRC. 1998. Nutrient Requirements of Swine (10th Ed.). National Academy Press. Washington, DC.

Peterson, B. A. 2008. Effects of birth weight on growth performance, tissue accretion, and carcass composition of barrows to 145 kg body weight. PhD Diss. University of Illinois, Urbana.

Puls, C. L. 2009. Effects of birth weight and paylean inclusion level on the growth performance, carcass characteristics, and fresh pork quality parameters of pigs. MS Thesis. University of Illinois, Urbana.

Rehfeldt, C, and G. Kuhn. 2006. Consequences of birth weight for postnatal growth performance and carcass quality in pigs as related to myogenesis. J. Anim. Sci. 84(E. Suppl.):E113-E123.

Schinckel, A. P., N. Li, P. V. Preckel, M. E. Einstein, and D. Miller. 2003. Development of a stochastic pig compositional growth model. Prof. Anim. Sci. 19:255-260.

Schinckel, A. P., M. E. Einstein, S. Jungst, C. Booher, and S. Newman. 2009. Evaluation of different mixed model nonlinear functions to describe the body weight growth of pigs of different sire and dam lines. Prof. Anim. Sci. 25:307-324.

Schinckel, A. P., R. Cabrera, R. D. Boyd, S. Jungst, C. Booher, M. Johnston, and M. E. Einstein. 2007. Impact of birth and body weight at twenty days on the postweaning growth of pigs with different weaning management. Prof. Anim. Sci. 23:197-210.

Strathe, A. B., A. Danfaer, H. Sorensen, and E. Kebreab. 2010. A multilevel nonlinear mixed-effects approach to model growth in pigs. J. Anim. Sci. 88:638-649.

Wolter, B. F., M. Ellis, B. P. Corrigan, and J. M. DeDecker. 2002. The effect of birth weight and feeding of supplemental milk replacer to piglets during lactation on preweaning and postweaning growth performance and carcass characteristics. J. Anim. Sci. 80:301-308.

TABLES

Table 12. Least-squares means for the effects of gender on growth performance.[1]

Item	Gender		SEM	*P*-value
	Barrows	Gilts		
Number of pens	12	12	-	-
Live weight, kg				
Birth	1.47	1.43	0.015	0.01
Weaning	5.0	5.0	0.10	0.85
Week 2	7.8	7.8	0.35	0.94
Week 4	13.1	13.1	0.70	0.99
Week 6	20.2	20.1	1.02	0.40
Week 8	30.0	29.7	1.50	0.18
Week 10	41.3	40.5	1.20	0.08
Coefficient of variation (within-pen), %				
Weaning	20.9	19.9	0.87	0.01
Week 2	21.7	19.9	0.79	0.00
Week 4	22.1	20.6	0.66	0.02
Week 6	21.2	20.3	0.60	0.11
Week 8	19.7	18.6	0.62	0.03
Week 10	18.2	17.0	0.74	0.02
Average daily gain, g				
Birth – weaning	168	170	6.2	0.44
Weaning - week 2[2]	195	196	14.7	0.92
Week 2 - week 4	376	377	25.3	0.85
Week 4 - week 6	497	491	24.1	0.44
Week 6 - week 8[3]	680	666	22.1	0.19
Week 8 - week 10[4]	780	749	27.6	0.09
Weaning - week 10	502	494	15.5	0.14
Morbidity and mortality, %	4.97	4.53	0.698	0.68

[1]Includes data from all 6 replicates (12 pens).
[2]Period was 14.2 days.
[3]Period was 14.3 days.
[4]Period was 14.5 days.

Table 13. Least-squares means for the effects of gender on growth performance.[1]

Item	Gender		SEM	*P*-value
	Barrows	Gilts		
Number of pens	6	6	-	-
Live weight, kg				
Birth	1.46	1.42	0.025	0.16
Weaning	5.2	5.1	0.07	0.05
Week 2	8.1	8.0	0.07	0.59
Week 4	13.6	13.6	0.11	0.78
Week 6	20.7	20.7	0.30	0.79
Week 8	30.7	30.5	0.45	0.66
Week 10	43.2	42.8	0.95	0.59
Week 12	53.0	50.9	0.77	0.18
Week 14	70.9	67.1	0.76	0.016
Week 16	85.6	80.3	0.60	0.005
Week 18	100.0	93.6	0.55	<0.001
Week 20	111.6	105.1	1.07	0.004
Week 22	123.7	116.0	0.47	<0.001
End of test	135.5	135.0	0.46	0.52
Coefficient of variation (within-pen), %				
Weaning	21.7	20.7	0.76	0.02
Week 2	21.5	20.0	0.68	0.04
Week 4	21.5	19.7	0.96	0.06
Week 6	20.7	19.4	1.12	0.35
Week 8	19.2	18.0	1.13	0.08
Week 10	17.4	16.2	1.15	0.09
Week 12	16.8	15.5	0.96	0.05
Week 14	14.9	14.1	0.79	0.01
Week 16	14.0	13.3	0.73	0.14
Week 18	12.6	12.2	0.65	0.45
Week 20	11.8	11.8	0.70	0.95
Week 22	10.5	11.2	0.61	0.22
End of test	10.0	10.1	0.42	0.80
Average daily gain, g				
Birth - weaning	165	163	2.7	0.17
Weaning - Week 2[2]	219	223	6.6	0.57
Week 2 - Week 4	392	398	10.1	0.15
Week 4 - Week 6	496	504	13.7	0.25
Week 6 - Week 8	705	691	11.1	0.47
Week 8 - Week 10[3]	773	765	37.0	0.66
Week 10 - week 12[4]	970	804	48.1	0.07
Week 12 - week 14[5]	1052	944	28.9	0.07
Week 14 - week 16	1045	932	21.7	0.07
Week 16 - week 18	1015	947	16.3	0.05
Week 18 - week 20	823	819	46.7	0.93
Week 20 - week 22	847	775	32.1	0.07
Week 22 - end of test	892	876	18.1	0.61
Weaning - week 10	525	525	12.3	0.98
Weaning - end of test	769	730	3.5	0.004
Week 10 - end of test	952	876	7.9	0.001
Morbidity and mortality, %	11.10	9.32	1.314	0.44

[1]Includes data from the 3 replicates that remained on test after week 10 post-weaning.
[2]Period was 13 days.
[3]Period was 16 days.
[4]Period was 10 days.
[5]Period was 17 days.

Table 14. Summary of regression equations for the prediction of instantaneous ADG for barrows and gilts.

		Dependent variable descriptive statistics		Parameter estimates[a]				Model statistics	
Item	Independent variable	Mean	Standard deviation	Intercept	Linear	Quadratic	Cubic	R^2	RSD[b]
Gender									
Barrows									
Dependent variable									
Average daily gain, g[c]									
Data set used:									
Individual pig data	Period mean live weight, kg	729	353.6	28.355	34.6329	-0.3721	0.001196	0.77	170.4
Pen mean data	Period mean live weight, kg	721	310.1	137.02	22.5632	-0.1375	NS	0.81	139.8
Standard deviation in live weight (within-pen), kg									
Weaning to week 10 post-weaning	Live weight, kg	3.89	2.359	-0.227	0.2616	-0.00182	NS	0.99	0.200
Week 10 post-weaning to end of test	Live weight, kg	11.39	2.373	0.560	0.1939	-0.00073	NS	0.96	0.500
Coefficient of variation in live weight (within-pen), %									
Weaning to week 10 post-weaning	Live weight, kg	20.7	1.95	22.420	-0.0903	NS	NS	0.66	1.14
Week 10 post-weaning to end of test	Live weight, kg	13.5	3.02	20.985	-0.0828	NS	NS	0.95	0.65
Gilts									
Dependent variable									
Average daily gain, g									
Data set used:									
Individual pig data	Period mean live weight, kg	698	312.8	75.291	30.2896	-0.3398	0.001171	0.71	169.6
Pen mean data	Period mean live weight, kg	680	265.9	174.53	19.1498	-0.1165	NS	0.83	112.6
Standard deviation in live weight (within-pen), kg									
Weaning to week 10 post-weaning	Live weight, kg	3.62	2.181	-0.242	0.2506	-0.00186	NS	0.99	0.239
Week 10 post-weaning to end of test	Live weight, kg	10.96	2.569	1.067	0.1573	-0.00048	NS	0.98	0.322
Coefficient of variation in live weight (within-pen), %									
Weaning to week 10 post-weaning	Live weight, kg	19.4	2.20	21.053	-0.0870	NS	NS	0.73	1.14
Week 10 post-weaning to end of test	Live weight, kg	12.7	2.47	18.667	-0.0651	NS	NS	0.96	0.50

[a]"NS" = not significant (*P* > 0.05).
[b]Residual standard deviation.
[c]One block (i.e., 1 pen of ~153 pigs from weaning to week 10 post-weaning, which was split into 2 pens from week 10 post-weaning to the end of test) of barrows was removed from both data sets as individual pig identification was lost towards the end of the study.

Table 15. Summary of multi-variable regression equations for the prediction of instantaneous ADG.

	Parameter statistics			Model statistics	
Parameters[a]	Estimate	Standard error	*P*-value	R^2	RSD[b]
Full model				0.72	173.9
Intercept	78.1791	27.8256	0.11	-	-
Gender	-36.6786	42.2080	0.38	-	-
BirthWt	-6.0262	19.2341	0.54	-	-
Gender*BirthWt	-5.8888	29.1235	0.84	-	-
BWlinear	28.2962	1.9947	<0.001	-	-
Gender*BWlinear	3.3487	3.0706	0.28	-	-
BirthWt*BWlinear	1.8116	1.3566	0.04	-	-
Gender*BirthWt*BWlinear	0.5657	2.0682	0.78	-	-
BWquad	-0.3621	0.03444	<0.001	-	-
Gender*BWquadratic	-0.02010	0.05300	0.70	-	-
BirthWt*BWquadratic	0.00652	0.02297	0.78	-	-
Gender*BirthWt*BWquadratic	-0.00802	0.03498	0.82	-	-
BWcubic	0.00146	0.000164	<0.001	-	-
Gender*BWcubic	-0.000052	0.000252	0.84	-	-
BirthWt*BWcubic	-0.000153	0.000108	0.16	-	-
Gender*BirthWt*BWcubic	0.000056	0.000163	0.73	-	-
Reduced model				0.72	174.0
Intercept	99.7937	16.9931	<0.001	-	-
Gender	-40.1892	7.6767	<0.001	-	-
BirthWt	-22.4790	11.3692	0.05	-	-
BWlinear	26.0137	0.6884	<0.001	-	-
Gender*BWlinear	3.7065	0.2986	<0.001	-	-
BirthWt*BWlinear	3.5058	0.4437	<0.001	-	-
BWquadratic	-0.3202	0.006968	<0.001	-	-
Gender*BWquadratic	-0.02439	0.002187	<0.001	-	-
BirthWt*BWquadratic	-0.02393	0.003288	<0.001	-	-
BWcubic	0.001248	0.000028	<0.001	-	-

[a]BirthWt = birth weight; Gender = 1 if barrow and 0 if gilt; BWlinear = linear coefficient for period mean live weight (i.e., the mean of the live weights at the start and end of each 2-week weigh period); BWquadratic = quadratic coefficient for period mean live weight; BWcubic= cubic coefficient for period mean live weight.

[b]Residual standard deviation.

Table 16. Correlation of live weight rank (within-pen).[1]

Item	Period 1 (n=1792)[2]			Period 2 (n=851)[3]			
	Birth	Weaning	Week 10 post-weaning	Birth	Weaning	Week 10 post-weaning	Week 22 post-weaning
Period 1 (n=1792)[2]							
Birth	1.00	0.54	0.51	-	-	-	-
Weaning	-	1.00	0.56	-	-	-	-
Week 10 post-weaning	-	-	1.00	-	-	-	-
Period 2 (n=851)[3]							
Birth	-	-	-	1.00	0.61	0.57	0.50
Weaning	-	-	-	-	1.00	0.60	0.51
Week 10 post-weaning	-	-	-	-	-	1.00	0.82
Week 22 post-weaning	-	-	-	-	-	-	1.00

[1]All shown correlation coefficients were significant ($P \leq 0.05$).
[2]Includes 10 pens of ~153 and 2 pens of ~175 pigs from weaning to week 10 post-weaning (excluding morbidities and mortalities).
[3]Includes 12 pens of ~73 pigs from week 10 post-weaning to end of test (excluding morbidities and mortalities).

Table 17. Number and percentage of pigs in each live weight quartile at birth, weaning, and week 10 post weaning that remained in the same live weight quartile in subsequent weight collection periods.[1]

	Live weight quartile at weaning				Live weight quartile at week 10 post-weaning				Live weight quartile at week 22 post-weaning			
Item	1	2	3	4	1	2	3	4	1	2	3	4
Live weight quartile at birth												
Number of pigs, n												
Quartile 1	107	57	20	7	96	52	31	12	95	46	40	10
Quartile 2	47	70	48	28	57	63	43	30	62	57	42	32
Quartile 3	31	45	65	53	25	56	60	53	27	54	56	57
Quartile 4	8	21	60	104	14	22	59	98	9	36	55	93
Percentage of pigs, %												
Quartile 1	55.4	29.5	10.4	3.6	50.0	26.9	16.1	6.2	49.2	23.8	20.7	5.2
Quartile 2	24.4	36.3	24.9	14.6	29.7	32.6	22.3	15.5	32.1	29.5	21.8	16.7
Quartile 3	16.1	23.3	33.7	27.6	13.0	29.0	31.1	27.5	14.0	28.0	29.0	29.7
Quartile 4	4.1	10.9	31.1	54.2	7.3	11.4	30.6	50.8	4.7	18.7	28.5	48.4
Live weight quartile at weaning												
Number of pigs, n												
Quartile 1	-	-	-	-	106	62	21	4	103	57	26	7
Quartile 2	-	-	-	-	51	67	57	18	49	65	54	25
Quartile 3	-	-	-	-	22	36	63	72	30	33	58	72
Quartile 4	-	-	-	-	13	28	52	99	11	38	55	88
Percentage of pigs, %												
Quartile 1	-	-	-	-	55.2	32.1	10.9	2.1	53.4	29.5	13.5	3.6
Quartile 2	-	-	-	-	26.6	34.7	29.5	9.3	25.4	33.7	28.0	13.0
Quartile 3	-	-	-	-	11.5	18.7	32.6	37.3	15.5	17.1	30.1	37.5
Quartile 4	-	-	-	-	6.8	14.5	26.9	51.3	5.7	19.7	28.5	45.8
Live weight quartile at week 10 post-weaning												
Number of pigs, n												
Quartile 1	-	-	-	-	-	-	-	-	134	48	9	1
Quartile 2	-	-	-	-	-	-	-	-	47	87	52	7
Quartile 3	-	-	-	-	-	-	-	-	9	51	87	46
Quartile 4	-	-	-	-	-	-	-	-	3	7	45	138
Percentage of pigs, %												
Quartile 1	-	-	-	-	-	-	-	-	69.4	24.9	4.7	0.5
Quartile 2	-	-	-	-	-	-	-	-	24.4	45.1	26.9	3.6
Quartile 3	-	-	-	-	-	-	-	-	4.7	26.4	45.1	24.0
Quartile 4	-	-	-	-	-	-	-	-	1.6	3.6	23.3	71.9

[1]Quartile 1 = lightest 25% of pigs in the pen; Quartile 2 = 2nd lightest 25% of pigs in the pen; Quartile 3 = 3rd lightest 25% of pigs in the pen; Quartile 4 = heaviest 25% of pigs in the pen.

FIGURES

Figure 16. Regression of instantaneous ADG against mean period live weight for barrows and gilts using individual and pen mean data.

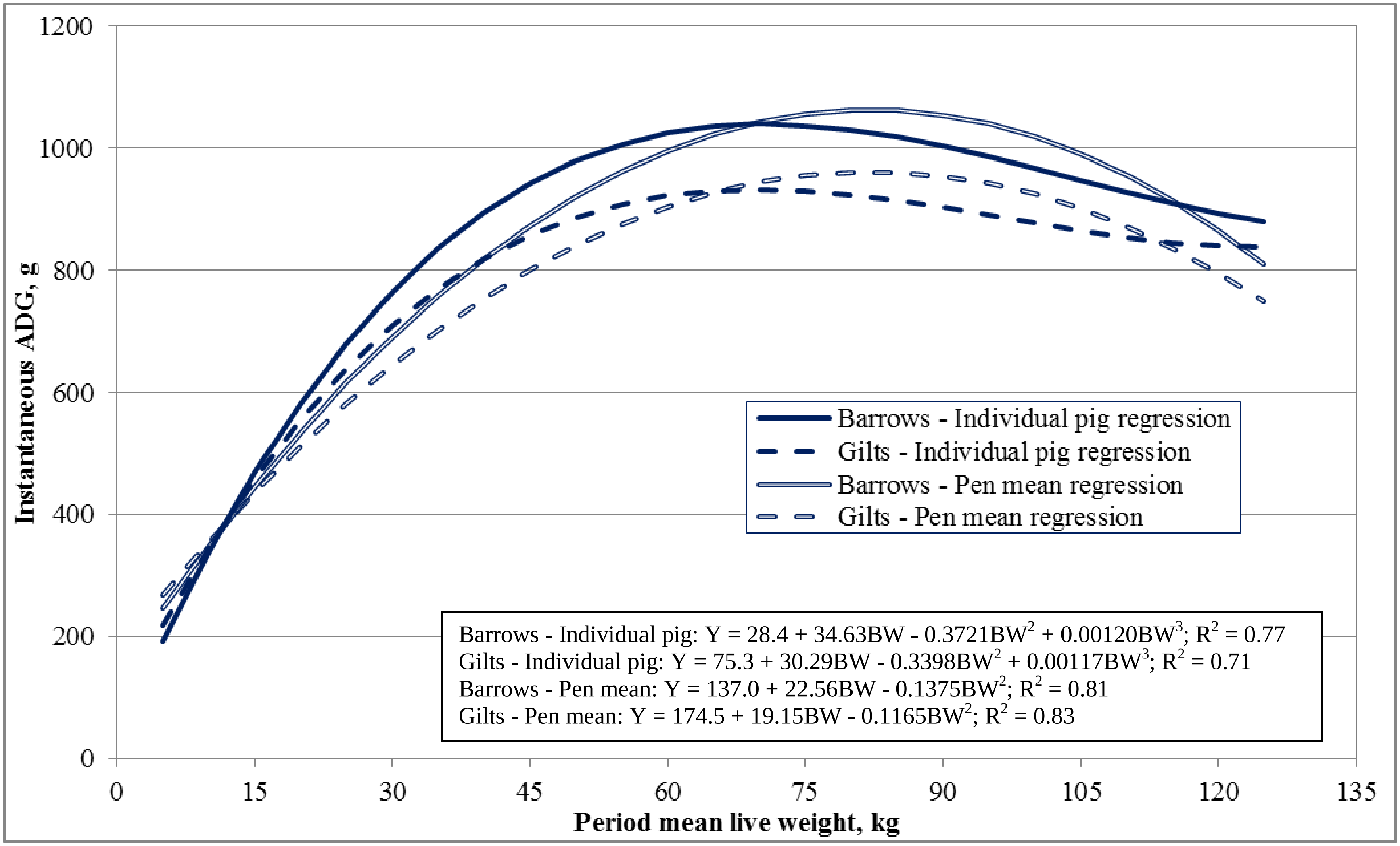


Figure 17. Predicted instantaneous ADG for barrows and gilts at various birth weights.

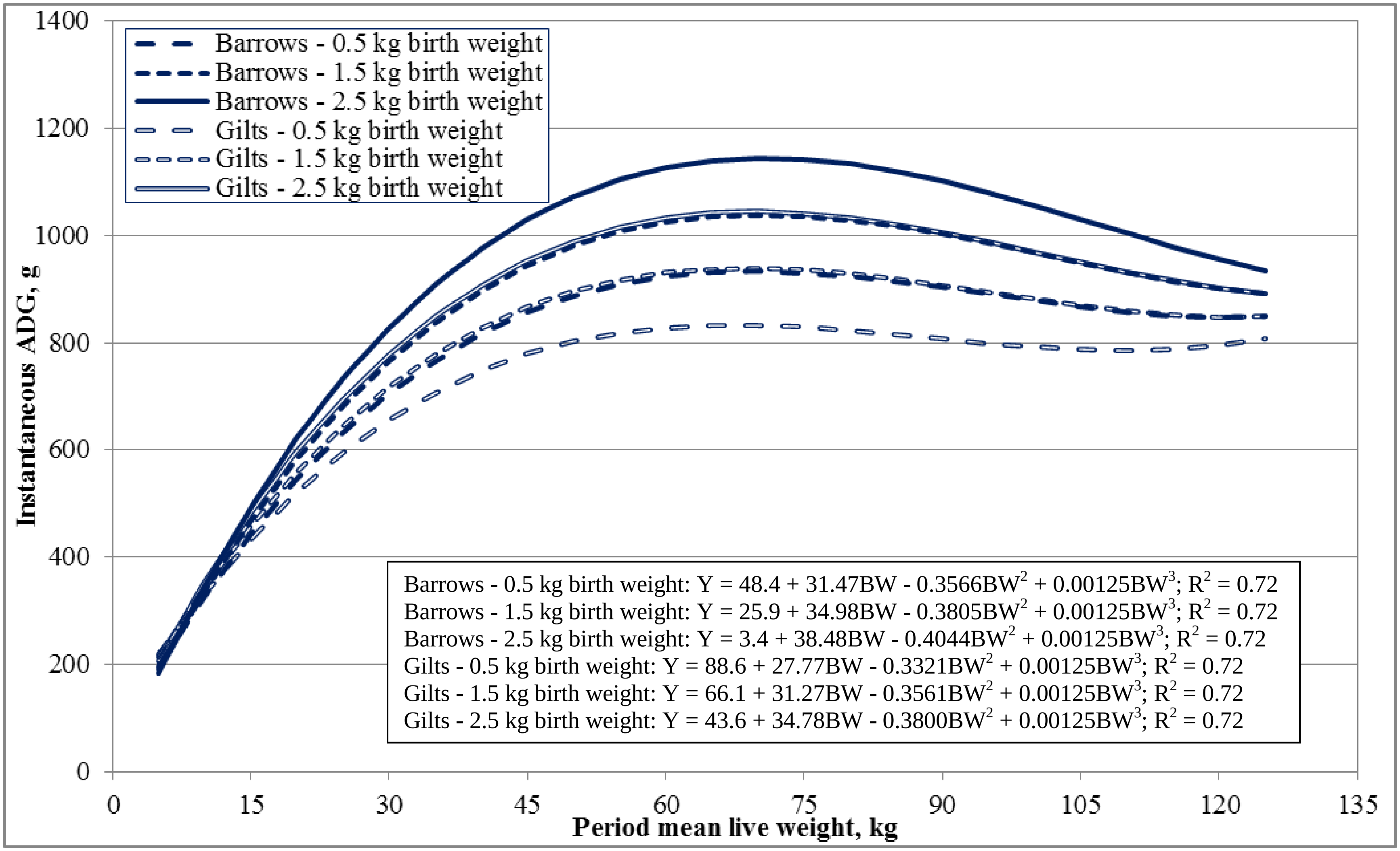


Figure 18. Regression of standard deviation of live weight against live weight for barrows and gilts from weaning to week 10 post-weaning.

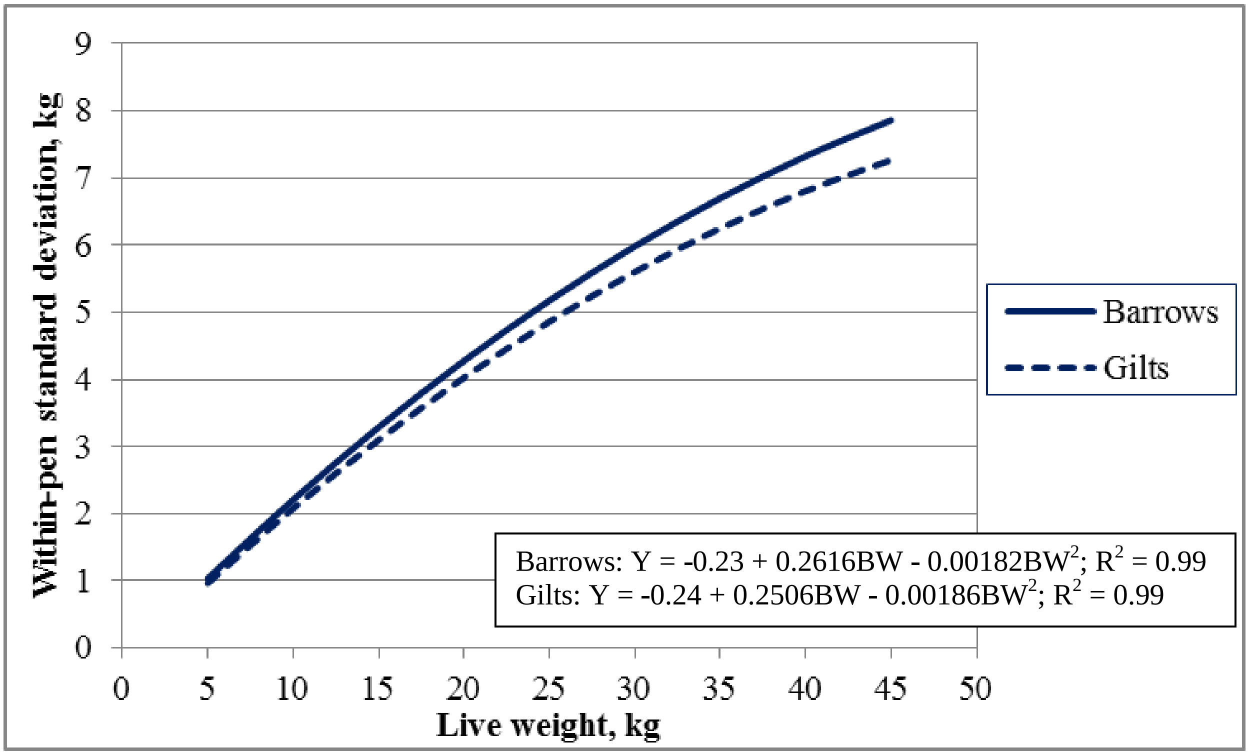


Figure 19. Regression of standard deviation of live weight against live weight for barrows and gilts from week 10 post-weaning to the end of test.

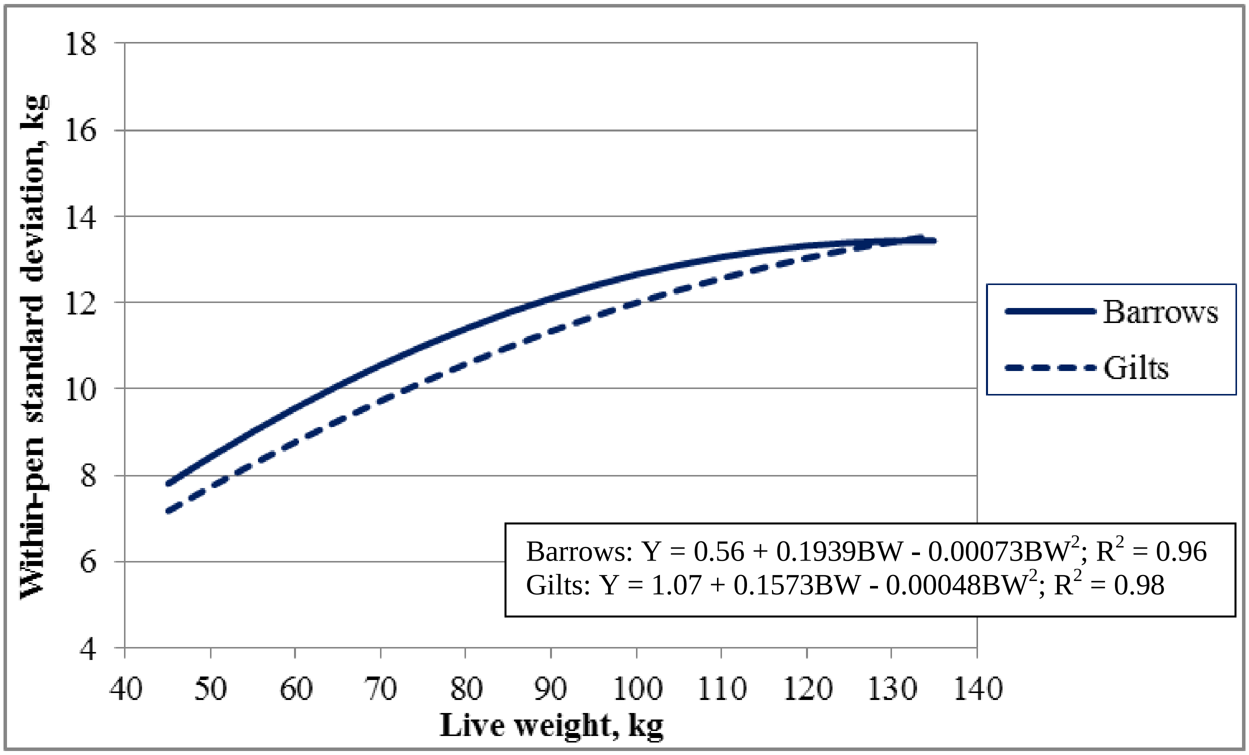


Figure 20. Regression of within-pen coefficient of variation in live weight against live weight for barrows and gilts from weaning to week 10 post-weaning.

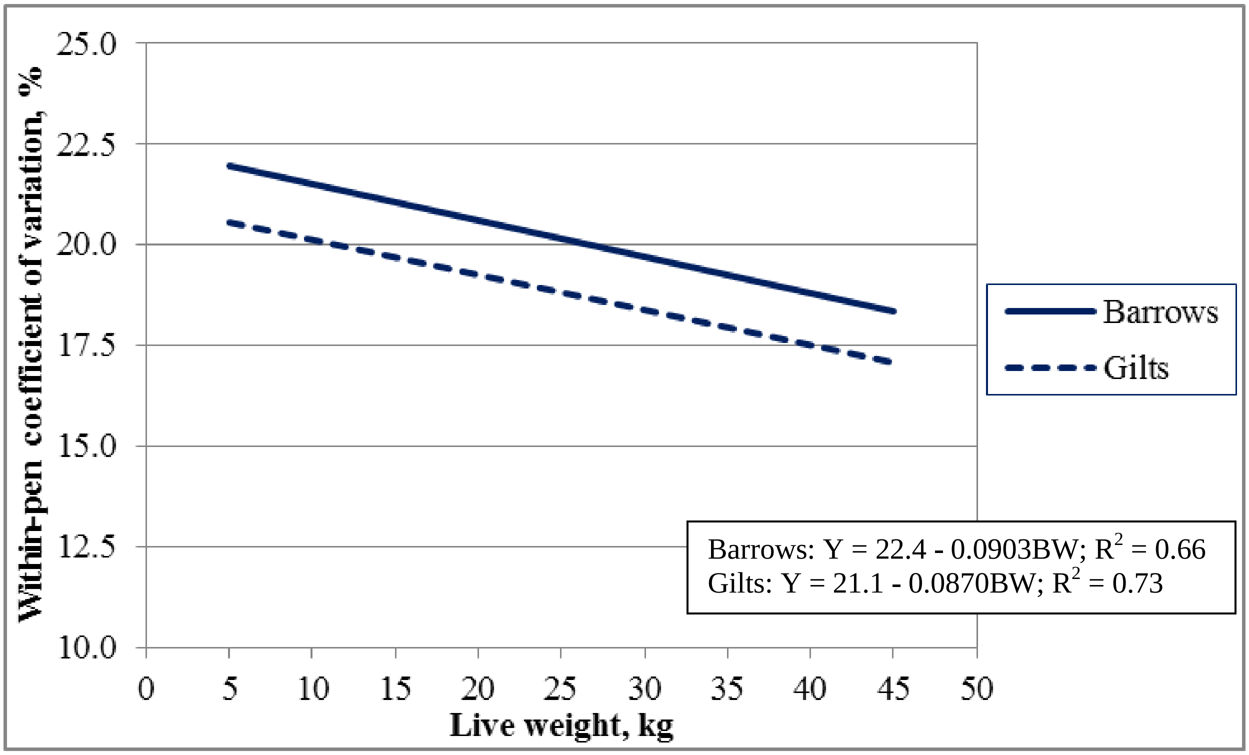
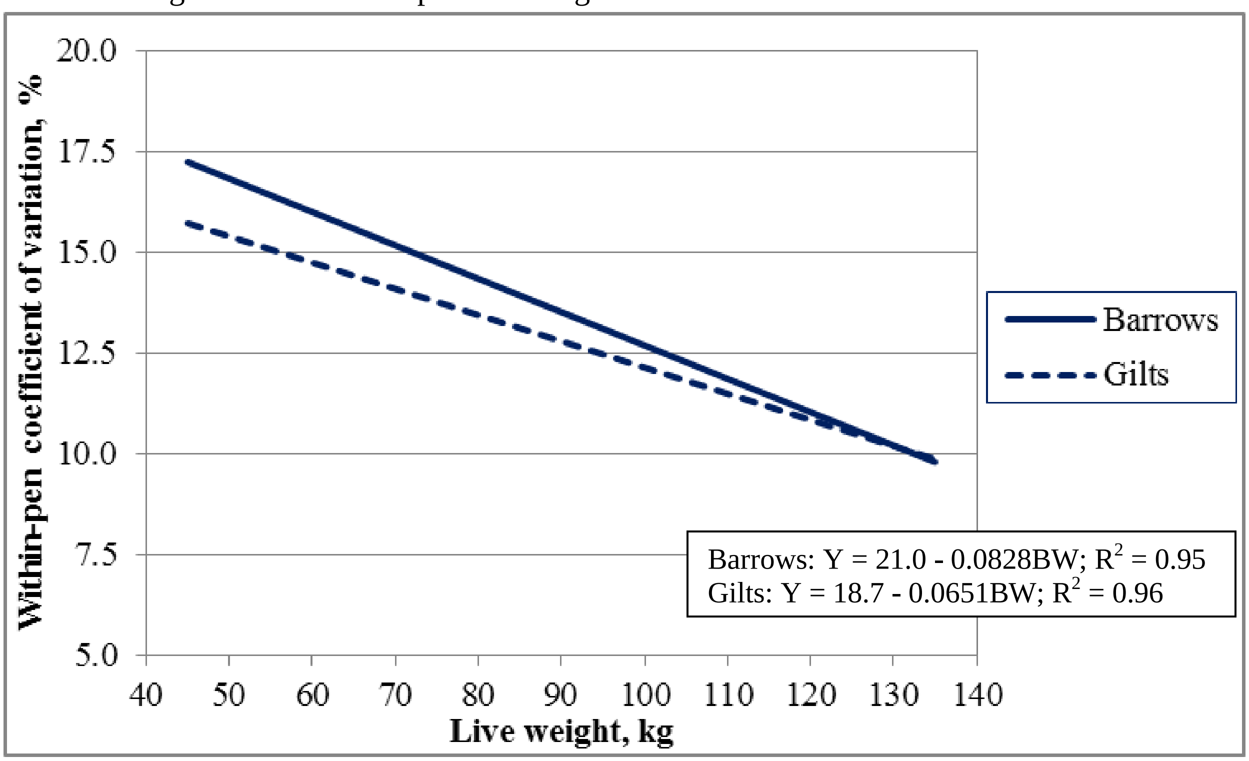


Figure 21. Regression of within-pen coefficient in live weight against live weight for barrows and gilts from week 10 post-weaning to the end of test.



CHAPTER 5: EVALUATION OF GROWTH EQUATIONS AND STRATEGIES FOR PREDICTING GROWTH PERFORMANCE AND WITHIN-PEN VARIATION IN LIVE WEIGHT.

ABSTRACT

A series of analyses were carried out with the following objectives: 1) Determine the equation that gives the best fit to live weight data as a function of days on test using 2 different data sets, 2) Determine the most appropriate method of modeling ADG, ADFI, and G:F, and 3) Evaluate the use of mixed models for predicting the within-pen variation in live weight for pigs reared in large groups. For Objective 1, the equations between live weight and days on test that were evaluated were the Logistic, von Bertalanffy, Gompertz, Richards, Generalized Michaelis-Menten (GMM), Bridges, and Polynomial. The first data set (data set 1) was from the study presented in Chapter 2 of this thesis and included 12 pens of 20 pigs reared from weaning to a pen mean live weight of 167.5 ± 3.30 kg. The second data set (data set 2) was from the 181 kg Harvest Weight treatment in the study presented in Chapter 3 of this thesis and included 16 pens of 20 pigs reared from weaning to a pen mean live weight of 159.7 ± 0.89 kg. In both data sets 1 and 2, group weights and feed intake were measured every 2 weeks from start to end of study. Data sets 1 and 2 were combined and used for Objective 2. Predictions of ADG were developed by using the derivative of the 7 equations between live weight and days on test and also by developing polynomial equations between period ADG and period mean live weight. Predictions of ADFI were developed using two approaches, firstly, by using the derivative of an equation between cumulative feed intake and days on test and, secondly, by developing polynomial equations between period ADFI and period mean live weight. Predictions of G:F were also developed using 2 approaches, firstly, by dividing each of the predictions of ADG by predicted ADFI and, secondly, by developing polynomial and logistic equations between period G:F and period mean live weight. For Objective 3, a third data set (data set 3) was used which

was from the study presented in Chapter 4 of this thesis which included 6 pens of 153 pigs reared from weaning to week 10 post-weaning that were each then split into 2 equal pens of approximately 73 pigs and reared from week 10 post-weaning to a mean live weight of 147.3 ± 2.51 kg. The Bridges and GMM equations were developed with 2 random effects for individual pigs as follows: Bridges equation: $BW_{it} = W_0+(W_m+w_i)*(1-\exp(-\exp(k+k_i)*t^a)) + e_{it}$; GMM equation: $BW_{it} = (W_0*(k+k_i)^a+(W_m+w_i)*t^a)/ ((k+k_i)^a+t^a) + e_{it}$; where BW_{it} is the body weight of the i^{th} pig at t days of age, W_0 is the actual birth weight of each pig, parameter W_m is the upper asymptote (i.e., an estimate of the mature live weight), parameters k and a are constants, parameter w_i is the random effect of the i^{th} pig on W_m, parameter k_i is the random effect of the i^{th} pig on k, e_{it} is the error term, and t is the days of age. The results of the 3 analyses suggest that the increase in pen mean live weight over time can be accurately described by a number of nonlinear equations; however, these equations may not be necessary as these results further suggest that growth performance can be described at least as accurately by simple polynomial or logarithmic equations between period growth performance measures and period mean live weight. In addition, predictions of within-pen variation developed using mixed models with random effects for individual pigs were generally inaccurate and lower than the actual within-pen variation. Alternative approaches for modeling the growth of individual pigs within pens should be evaluated.

INTRODUCTION

A number of equations have been evaluated for describing the growth (Kebreab et al., 2007; Strathe et al., 2010) and feed intake (Whittemore et al., 1983; Quiniou et al., 2000) of pigs; however, these equations were developed using data from studies that were carried out in controlled research environments, were limited in size, and/or used relatively light pigs (i.e., live weights that were not significantly above the current US industry average harvest weight). Few studies have evaluated the mathematical modeling of feed efficiency. In addition, most studies that have developed growth equations have used data from individual pigs rather than the mean of a pen of pigs, which is commonly used as the experimental unit in commercial research. Nevertheless, when modeling the mean growth performance of a pen of pigs, it is still important to understand the amount of variation in live weight within a pen around the mean. Statistical software programs that allow for the use of mixed models (i.e., models with both fixed and random effects) have been used to estimate the variation in live weight within a population of pigs (Schinckel et al., 2003); however, these have not been used to estimate within-pen variation in live weight. Therefore, the objectives of this study were, for pigs reared to heavy weights in a commercial wean-to-finish facility, to: 1) Determine the equation that gives the best fit to the live weight data as a function of days on test using 2 different data sets, 2) Determine the most appropriate method of modeling ADG, ADFI, and G:F, and 3) Evaluate the use of mixed models for predicting the within-pen variation in live weight for pigs reared in large groups.

MATERIALS AND METHODS

A series of analyses were carried out in two parts using data sets from Chapters 2, 3, and 4 of this thesis. In Part 1, growth equations between live weight and days on test and different methods of predicting ADG, ADFI, and G:F were evaluated. In Part 2, the use of mixed models for the prediction of live weight variation within pens of pigs across a range of live weights was evaluated. The data sets used in these analyses are summarized in Table 18 below.

Table 18. Summary of data sets.

Data set	Source	Start of study	End of study	Type of measurement	Group size	Number of pens
Part 1						
Data set 1	Chapter 2	Weaning	167.5 ± 3.30 kg[1]	Pen mean	20	12
Data set 2	Chapter 3	Weaning	159.7 ± 0.89 kg[1]	Pen mean	20	16
Part 2						
Data set 3[2]	Chapter 4	Birth	147.3 ± 2.51 kg[3]	Individual pig	Period 1: ~153 Period 2: ~73	Period 1: 6 Period 2: 11

[1]Represents a pen mean live weight.
[2]For Data set 3, Periods 1 and 2 were from weaning to week 10 post-weaning and week 10 post-weaning to the end of study, respectively.
[3]Represents the mean live weight of all individual pigs within a pen as they were taken off test and removed from the pens for harvest.

Part 1. Evaluation of Growth Equations and Methods for Predicting Growth Performance (Objectives 1 and 2).

The objectives of this part were to: 1) Determine the equation that gave the best fit to the live weight data as a function of days on test using 2 different data sets, 2) Determine the most appropriate method of modeling ADG, ADFI, and G:F.

Data sets

Data sets 1 and 2, as well as the two data sets combined, were used to address Objective 1. The two data sets (1 and 2) combined were used to address Objective 2. Data set 1 was the pen mean growth performance measured on 12 single-gender pens (6 pens of barrows and 6 pens of gilts) from the study reported in Chapter 2 of this thesis. Data set 2 was the pen mean growth performance measured on 16 single-gender pens (8 pens of barrows and 8 pens of gilts) from the heaviest Harvest Weight treatment of the study reported in Chapter 3 of this thesis (excluding all data collected after the first pigs were removed from pens for harvest).

The studies from which data sets 1 and 2 originated both used pigs that were the progeny of PIC 359 sires mated to PIC C22 or PIC C29 dams (PIC, Hendersonville, KY). Dam line was not taken into account in the allotment of pigs to the either study because the litter of origin of the pigs was not known. Pigs were housed in groups of 20 and provided a floor space of 1.06 m^2/pig. In the event of a mortality or removal of a morbid pig during both studies, pen size was adjusted using a moveable partition to maintain the correct floor space. Each pen was equipped with one 5-hole wet/dry box feeder (Feed Ease Wet/Dry Feeder, A. J. O'Mara Group, Lyons, NE) mounted in the fence line. One feeder hole was covered, providing only 4 holes with 142.2 cm of feeder trough space (7.1 cm/pig). An additional cup-type water drinker was provided in each pen. Pigs were provided ad libitum access to feed and water. An 8-phase dietary program was used and diets were formulated to meet or exceed NRC (1998) recommendations for nutrient requirements for pigs across the weight range used. The final dietary phase, which was fed from approximately 115 kg live weight to the end of test, was formulated to the requirement of a 115 kg pig.

In both studies, group weights were collected every 2 weeks from the start to the end of study, and feed intake was measured each time the pigs were weighed. Pigs experiencing either health problems or injuries that did not respond to treatment were removed from the study and the date of, pig weight at, and reason for removal were recorded; the weight of pigs removed was included in the calculation of growth rate and gain:feed ratio. The least-squares means for the effects of gender on growth performance which was reported in Chapter 2 (i.e., data set 1) is presented in Table 20 and the descriptive statistics for the heaviest Harvest Weight treatment from the study reported in Chapter 3 (i.e., data set 2) is presented in Table 21.

Procedures

The following 7 different growth functions (Table 19) were evaluated for fitting pen mean live weights as a function of days on test:

Logistic: $W_m/(1+a*\exp(-k*t))$

von Bertalanffy: $W_m*(1-a*exp(-k*t))^3$

Gompertz: $W_m*exp(-a*exp(-k*t))$

Richards: $W_0*W_m/(W_0^a+(W_m^a-W_0^a)*exp(-k*t))^{1/a}$

Generalized Michaelis-Menten (GMM): $(W_0*k^a+W_m*t^a)/(k^a+t^a)$

Bridges: $W_0+W_m*(1-exp(-exp(k)*t^a))$

Polynomial: $W_0+b_1*t+b_2*t^2+b_3*t^3$

Where: W_0 is the pen mean live weight at weaning, parameter W_m is the upper asymptote (i.e., an estimate of mature live weight), parameters k and a are constants that determine the shape of the curve, parameters b_1, b_2, and b_3 are the linear, quadratic, and cubic coefficients for the polynomial equation, respectively, and t is days on test. In addition, each equation included a single random effect for pen as follows:

$BW_{i,t} = (1+p_i)$*Growth Equation

Where: $BW_{i,t}$ is the mean live weight of the i^{th} pen at t days on test and p_i is a random effect for the i^{th} pen.

Predictions of ADG were developed across the range of weights evaluated using 2 different approaches. Firstly, ADG was predicted using the first-order derivative of the equations developed above between pen mean live weight and days on test. Alternatively, ADG was predicted by developing polynomial regression equations between period ADG and period mean live weight. Period ADG and period mean live weight were calculated as follows:

Period ADG = [(total pen weight at end of period – total pen weight at start of period + weight of pigs removed during period) / (number of pigs at end of period * number of days between start and end of period + sum of all the days the pigs removed were in the pen since the start of the period)].

Period mean live weight = [(mean live weight of pen at start of period + mean live weight of pen at end of period) / 2].

Equations to predict ADFI were also developed across the range of weights evaluated using 2 different approaches. The first approach was to develop a polynomial regression equation between cumulative feed intake and days on test. The first-order derivative of that equation resulted in an equation between ADFI and days on test. Similar to ADG, the second approach was to develop a polynomial regression equation between period ADFI and period mean live weight. Period ADFI was calculated as follows:

Period ADFI = [(total feed consumed during the period) / (number of pigs at end of period * number of days between start and end of period + sum of all the days the pigs removed were in the pen since the start of the period)].

Equations to predict G:F were developed by, firstly, dividing predicted ADG developed from each of the methods described above by predicted ADFI developed from the 2 methods described above and, secondly, by developing regression equations between period G:F and period mean live weight. Period G:F was calculated as follows:

Period G:F = Period ADG / Period ADFI.

In order to calculate the bias at different parts of each of the live weight curves over time for data sets 1 and 2, the mean of the residuals was calculated for the following 3 periods: 1) Period 1 (weaning to 60 kg live weight); 2) Period 2 (60 to 110 kg live weight); and 3) Period 3 [110 kg live weight to the end of study (167.5 and 159.7 kg in data set 1 and 2, respectively)]. Bias was calculated over the same periods as above for all growth performance curves, only period mean live weights were used to separate the data into periods instead of live weights. For live weight predictions, residuals were calculated for each pen for each weigh period by subtracting the actual live weight from the predicted values at the specific weigh periods.

Residuals for predictions of growth performance developed using the derivative of the equations relating either live weight or cumulative feed intake with days on test were calculated by subtracting the actual period growth performance from the growth performance predictions at the time halfway between the start and end of each weigh period. Residuals for predictions of growth performance developed by equations between period growth performance and period mean live weight were calculated by subtracting the actual period growth performance measures from the predicted growth performance.

<u>Part 2. Prediction of Within-Pen Live Weight Variation (Objective 3).</u>

The objective of this part was to evaluate the use of mixed models for predicting the within-pen variation in live weight for pigs reared in large groups.

Data Set

Data set 3 was used in this analysis and came from the study reported in Chapter 4 of this thesis. The study was carried out in 2 periods. Periods 1 and 2 were from weaning to week 10 post-weaning and from week 10 post-weaning to a pen mean live weight of ~135 kg, respectively. Only pigs used in both periods were included in the data set, which consisted of 920 pigs in 6 pens (3 pens of barrows and 3 pens of gilts) with ~153 pigs per pen during Period 1. At the start of Period 2, each pen from Period 1 was split into 2 equal groups with a similar mean live weight and variation in live weight to form 12 pens. Several of the tags were missing from 1 of the 6 pens of barrows and, therefore, the entire pen was removed from the data set.

Pigs were the progeny of PIC 359 sires mated to PIC C29 dams (PIC, Hendersonville, KY). Each pen was equipped with two 4-hole wet/dry box feeders (Feed Ease Wet/Dry Feeder, A. J. O'Mara Group, Lyons, NE) with access to only one side of each feeder which provided 284.5 cm of feeder trough space (approximately 1.8 and 3.9 cm/pig from weaning to week 10 post-weaning and week 10 post-weaning to end of test, respectively). Two additional water cups were available in each pen. Pigs had ad libitum access to feed and water. An 8-phase dietary program was used and diets were formulated to meet or exceed NRC (1998) recommendations for nutrient requirements of pigs across the range of weights evaluated.

Pigs were weighed individually at birth and every 2 weeks from weaning to the end of test. All pigs that were removed from the study due to morbidity or mortality were excluded from the data set used to develop the growth curves. It was difficult to develop the nonlinear sigmoidal shaped growth curves for each individual pig and after several attempts, no reasonable solution for the parameter estimates was found. This difficulty was due partly to the fact that the end of study was a pen mean live weight of 135 kg. As a result, some of the pigs in each pen were below 100 kg in live weight and had very few data points, if any, above the live weight at which maximum instantaneous ADG occurs. These sigmoidal-shaped growth equations require that ADG increases up to a maximum and then subsequently decreases as the pig increases in age. Therefore, in order to develop these equations, sufficient live weight data must be available before, during, and after the time at which maximal ADG occurs. Although not reported in Chapter 4, individual pig weights were also collected every 2 weeks after the end of the study (i.e., at a pen mean live weight of 135.2 ± 0.76 kg) and at the time each pig was removed from a pen for harvest. These weights were included in the data set in order to obtain more data points during and after the time of maximal ADG for the lighter pigs within the pens. Pigs were removed from the pens for harvest according to the following schedule:

Start of harvest or end of growth study: Heaviest 10 %

Day 7: Next heaviest 20%

Day 14: Next heaviest 20%

Day 21: Next heaviest 20%

Day 28: Next heaviest 10%

Day 35: Lightest 20%

Procedures

Mixed models were used to develop separate growth curves for each individual pig. The Bridges and GMM equations have been used in studies reported in the literature to develop individual pig growth curves (Schinckel et al., 2009a) and, therefore, were used in this analysis. Each equation was fitted to the individual pig live weight data as a function of days of age. Two random effects (w_i and k_i) were included for the Bridges and GMM equations as follows:

Bridges equation: $BW_{it} = W_0+(W_m+w_i)*(1-\exp(-\exp(k+k_i)*t^a)) + e_{it}$

GMM equation: $BW_{it} = (W_0*(k+k_i)^a+(W_m+w_i)*t^a)/((k+k_i)^a+t^a) + e_{it}$

Where: BW_{it} is the body weight of the i^{th} pig at t days of age, W_0 is the actual birth weight of each pig, parameter W_m is the upper asymptote (i.e., an estimate of mature live weight), parameters k and a are constants, parameter w_i is the random effect of the i^{th} pig on W_m, parameter k_i is the random effect of the i^{th} pig on k, e_{it} is the error term, and t is the days of age.

Using the mixed models, live weight was predicted for each individual pig for each time that the pigs were weighed. For each pen at every weigh time, the mean, standard deviation (SD), and coefficient of variation (CV) of the predicted live weights was calculated and compared to the actual pen mean live weight and within-pen SD and CV in live weight. For each weigh time, residuals for the prediction of pen mean live weight and within-pen SD and CV in live weight were calculated by subtracting the actual values from the predicted values and the mean of those residuals represented the prediction bias.

Statistical Analysis

All equations were developed separately for each gender using the PROC NLMIXED procedure of SAS. The coefficient of determination (R^2), residual standard deviation (RSD), and Akaike's Information Criterion (AIC) were calculated and used to identify the equations that provided the best fit to the data. For the polynomial equations, the quadratic and cubic coefficients were only included in the model if they were found significant ($P \leq 0.05$) by the log-likelihood test. The PROC UNIVARIATE procedure of SAS was used to determine if prediction biases were different ($P \leq 0.05$) from zero. The PROC MIXED procedure of SAS was used to compare biases between the different growth equations and methods of predicting growth performance, and if the variances of the biases between either growth equations or methods of predicting growth performance were found different ($P \leq 0.05$) by the Brown-Forsythe test, the REPEATED option within PROC MIXED was used to fit separate variances for each equation or method.

RESULTS AND DISCUSSION

A summary of data sets 1, 2, and 3 are presented in Tables 20, 21, and 22, respectively. The results of the analyses from Part 1 are presented in Tables 23 to 29 and illustrated graphically in Figures 22 to 29 and those from Part 2 are presented in Tables 30 to 33.

Part 1. Evaluation of Growth Equations and Methods for Predicting Growth Performance (Objectives 1 and 2).

Objective 1: Determine the equation that gives the best fit to the live weight data as a function of days on test using 2 different data sets.

The parameter estimates and measures of goodness of fit for all 7 growth equations are presented in Table 23, prediction biases for the 7 equations are presented in Table 24, and the predictions of live weight are displayed graphically for barrows and gilts in Figures 22 and 23, respectively. For data sets 1 and 2 and both data sets combined, all 7 equations had very high R^2 (≥ 0.997); however, the Logistic and von Bertalanffy equations generally had higher RSD and AIC values than the other equations, which were all relatively similar (Table 23). For both data sets, prediction biases were generally more variable between equations during period 1 (i.e., from weaning to 60 kg live weight) than periods 2 and 3 (i.e., from 60 to 110 kg and 110 kg to the end of study, respectively; Table 24). For data sets 1 and 2, the von Bertalanffy, Gompertz, GMM, and Bridges equations generally had biases not different ($P > 0.05$) from zero for both genders across the 3 periods (Table 24). For both data sets, the Logistic, Richards, and Polynomial equations generally had positive biases (i.e., predicted values greater than actual values) during period 1, negative biases (i.e., predicted values lower than actual values) during period 2, and biases not different ($P > 0.05$) from zero during period 3 (Table 24). However, with the exception of the Logistic equation, biases for each equation were numerically less than 1 kg (Table 24). These results suggest that several equations described the increase in pen mean live weight over time reasonably accurately with minimal bias in the live weight predictions.

Of the 6 nonlinear growth equations (i.e., the Logistic, von Bertalanffy, Gompertz, Richards, GMM, and Bridges equations), the Logistic, von Bertalanffy, and Gompertz equations all have a fixed point of inflection (i.e., the maximum growth rate occurs at a fixed percentage of the mature live weight), whereas the other 3 equations have variable points of inflection (i.e., maximum growth rate can occur at various percentages of the mature live weight). For the Logistic, von Bertalanffy, and Gompertz equations, the maximum growth rate always occurs at 50.0, 36.8, and 29.6% of the mature live weight, respectively. Therefore, the higher RSD and AIC values for the Logistic and von Bertalanffy equations compared to the other equations could be contributed to an actual point of inflection different than 50.0 and 36.8% of the mature live weight, respectively.

For the nonlinear equations, the von Bertalanffy and GMM equations gave the greatest estimate of W_m, which is an estimate of the mature live weight (Table 23). Other studies carried out with individual pig data instead of pen means have reported comparable estimates of W_m and have also shown that the GMM equation produced higher estimates of mature live weight than the Bridges and other equations (Schinckel et al., 2006; Schinckel et al., 2009a). Specifically, Schinckel et al. (2006) reported estimates of W_m for the Bridges and GMM equations of 200.8 and 301.4 kg, respectively, for barrows and 191.4 and 286.8 kg, respectively, for gilts. Schinckel et al. (2009a) reported estimates of W_m of 211.9, 238.7, and 379.3 kg for the Gompertz, Bridges, and GMM equations, respectively. However, both of these studies were carried out using pigs reared to live weights well below the estimates of mature live weight and, therefore, these estimates are likely not very accurate. The actual mature live weight of pigs has not been clearly established. Strathe et al. (2010) recently reared 11 barrows and 13 gilts to live weights in excess of 300 kg and, using the GMM equation, reported estimates of W_m of 466.3 and 382.1 kg for barrows and gilts, respectively. This suggests that the von Bertalanffy and GMM equations may provide more realistic estimates of the mature live weight than the other equations. In addition, Schinckel et al. (2009a) suggested that the GMM equation is non-symmetric and allows for a more gradual decline in growth rates as live weights increase above that at which maximal ADG occurs. Nevertheless, in the current analyses, there is no indication that the GMM equation had superior goodness of fit when compared to the other equations.

Objective 2: Determine the most appropriate method of modeling ADG, ADFI, and G:F.

Parameter estimates and measures of goodness of fit for all equations relating period mean live weight and period ADG, ADFI, and G:F are presented in Table 25. Parameter estimates and measures of goodness of fit for equations between cumulative feed intake and days on test are presented in Table 26. Prediction biases for the different methods of predicting ADG, ADFI, and G:F are presented in Tables 27 to 29, respectively, and are illustrated graphically in Figures 24 to 29.

For the polynomial equations between period ADG and period mean live weight, the linear, quadratic, and cubic coefficients were all significant ($P \leq 0.05$; Table 25). For both genders, method of prediction had a significant ($P \leq 0.05$) impact on the prediction bias during period 1 (from weaning to a period mean live weight of 60 kg), period 2 (between period mean live weights of 60 and 110 kg), and period 3 (from a period mean live weight of 110 kg to the end of study; Table 27). Calculating ADG by using the derivatives of the Logistic and von Bertalanffy equations (methods 1 and 2 in Table 27, respectively) were the only 2 methods that resulted in biases different ($P \leq 0.05$) from zero in all 3 periods for both genders. This is not surprising as those 2 equations provided the poorest fit to the live weight data as a function of days on test (Table 23). The remaining 6 methods of predicting ADG are displayed graphically in Figures 24 and 25 for barrows and gilts, respectively. For gilts, with the exception of the derivative of the Gompertz equation (method 3 in Table 27) in period 1, all 6 remaining methods of predicting ADG (methods 3 to 8 in Table 27) resulted in biases that were not different ($P > 0.05$) from zero in all 3 periods (Table 27). For barrows, of the remaining 6 prediction methods, the derivative of Gompertz equation had the only bias different ($P \leq 0.05$) from zero in period 1, the derivative of the Gompertz, GMM, and Polynomial equations (methods 3, 5, and 7 in Table 27, respectively) all had negative biases different ($P \leq 0.05$) from zero in period 2, and the derivative of the GMM equation was the only method that had a bias that was different ($P \leq 0.05$) from zero in period 3. The derivative of the Richards and Bridges equations (methods 4 and 6 in Table 27, respectively) and the polynomial equation between period ADG and period mean live weight (method 8 in Table 27) were the only methods that did not ($P > 0.05$) have any biases different from zero for either gender in any period (Table 27).

Most, if not all, published studies which have suggested the use of nonlinear equations between live weight and days on test to model live weight change over time have used data from individual pigs to model the growth of the population rather than data from mean of a pen of pigs as was done in the current study (Craig and Schinckel, 2001; Schinckel et al., 2003; Schinckel et al., 2009a; Strathe et al., 2010). One potential issue with using pen mean data to develop equations between live weight and days on test is the failure to account for weight of morbidities and mortalities. For instance, if a light pig within the pen was removed, the mean live weight of the pen would increase. If ADG is simply measured by the difference in the mean live weights between periods, as is the case when the derivatives of the equations between live weight and days on test are used to predict ADG, and a light pig was removed from the pen, the ADG between those periods would be biased. Ideally, the weight and feed consumed by every pig removed from the pen due to morbidity or mortality should be removed from the data set; however, individual pig weight and feed intake is difficult to collect and rarely measured in research studies carried out in commercial facilities with pens of pigs. In this analysis, the weight and number of days in the pen for any pig removed is accounted for in the calculation of period ADG and, therefore, for studies with high rates of morbidity and mortality, equations between period ADG and period mean live weight should provide more accurate predictions of ADG. In data sets 1 and 2, morbidity and mortality rates were 5.4 and 5.3%, respectively. Nevertheless, if the weight of the morbidities and mortalities is similar to the mean live weight of the pen at the time of removal, the derivative of the growth equations between pen mean live weight and days on test should still provide accurate estimates of ADG. The results of the current analysis suggest a minimal prediction bias (< 0.05 kg in all 3 periods; Table 27) occurred when the derivatives of the Gompertz, Richards, GMM, Bridges, and Polynomial equations between live weight and days on test were used to predict ADG; however, the issue of accounting for the weight of mortalities and morbidities should be considered when developing growth equations using pen mean data.

Period ADFI increased ($P \leq 0.05$) quadratically for barrows and cubically for gilts as period mean live weight increased (Table 25). In addition, cumulative feed intake increased cubically for both barrows and gilts as days on test increased (Table 26). In general, the derivative of the polynomial equation between cumulative feed intake and days on test (method 1 in Table 28) resulted in a positive bias in periods 1 and 3 and a negative bias in period 2 for both genders ($P \leq 0.05$; Table 28 and Figures 26 and 27 for barrows and gilts respectively). The polynomial equation between period ADFI and period mean live weight (method 2 in Table 28) had no significant bias ($P > 0.05$) in any period and, therefore, was used in all calculations of G:F that involved predicted ADFI (i.e., methods 1 to 8 in Table 29). Other mathematical equations that have an upper asymptote have been suggested for modeling ADFI in Whittemore et al. (2001). However, most of the studies used to develop those equations reared pigs to lighter weights than in the current studies and, as a results, daily feed intake continued to increase or plateau as live weight increased. In the current studies, ADFI began to decline at live weights above 120 kg (Figure 26 and 27 for barrows and gilts, respectively). As a result, all equations of the form that have an upper asymptote were inappropriate for predicting feed intake in this analysis.

Feed efficiency was predicted by dividing each of the predictions of ADG by predicted ADFI and also by developing equations between period G:F and period mean live weight. Prediction biases for each of these methods are presented in Table 29. In Table 29, methods 1 to 7 are developed by dividing predicted ADG developed using the derivative of the Logistic, von Bertalanffy, Gompertz, Richards, GMM, Bridges, and Polynomial equations between live weight and days on test by Predicted ADFI, respectively, method 8 is developed by dividing predicted ADG developed from the polynomial equation between period ADG and period mean live weight by predicted ADFI, and methods 9 and 10, are by developing polynomial and logarithmic equations between period G:F and period mean live weight, respectively. For both genders, method of prediction had a significant ($P \leq 0.05$) impact on the prediction bias in all 3 periods

(Table 29). In general, the absolute value of the prediction biases for both genders in period 1 for methods 1, 2, 3, 5, and 6 were large (> 0.02 kg:kg; Table 28) and, therefore, will not be discussed in further detail. Method 7 was the only method which had no significant ($P \leq 0.05$) bias in either period for barrows and gilts; however, this method also had a numerically large negative bias (-0.031 kg:kg; $P = 0.09$) in period 1 for barrows and large standard errors during the period 1 for both barrows and gilts (Table 28).

All 4 remaining methods (methods 4, 8, 9, and 10) did not have a bias with an absolute value greater than 0.015 kg:kg in either period for either gender and had numerically small standard errors (Table 29). In order to describe the results of these methods in more detail, predictions of G:F developed from these 4 methods are illustrated graphically in Figures 28 and 29 for barrows and gilts, respectively. As shown in Figures 28 and 29, all 4 methods generally appear to have provided predictions of G:F similar to the actual period G:F across the entire range of weights evaluated. In some instances, there may be an advantage to being able to predict G:F directly from a single equation rather than from the division of 2 other predictions. Between the polynomial and logarithmic equations relating period G:F and period mean live weight (methods 9 and 10 in Table 29, respectively), the logarithmic equation had lower RSD and AIC (Table 25), which suggests a better fit. Schinckel et al. (2009b) modeled G:F by dividing predicted ADG by predicted ADFI; however, there have been no studies which have actually compared methods of predicting G:F. The results of this analysis suggest that G:F can be predicted accurately by dividing accurate predictions of ADG by accurate predictions of ADFI and by developing simple equations between period G:F and period mean live weight.

It is important to note that the process of fitting nonlinear equations was difficult and may not be appropriate in some situations. In addition, equations between period growth performance and period mean live weight generally provided as good if not more accurate predictions of growth performance. A major assumption when using equations between period growth performance and period mean live weight to predict performance as a function of live weight is that the period mean live weight and period growth performance are equal to the actual live weight and growth performance at the midpoint in time between the start and end of the period. In other words, it is assumed that live weight and growth performance measures increase linear between the start and end of a period. This assumption is reasonably valid when the number of days between the start and end of a period is relatively small as was the case in the current analysis (i.e., 14 days); however, for data sets in which performance was measured less frequently (e.g., less than once every 2 or 3 weeks), this may not be a valid assumption.

Part 2. Prediction of Within-Pen Live Weight Variation (Objective 3).

The parameter estimates, standard errors, and measures of goodness of fit for the Bridges and GMM equations between live weight and days on test are presented in Table 30 and the biases for the predictions of pen mean live weight and within-pen SD and CV in live weight are presented in Tables 31, 32, and 33, respectively. The Bridges and GMM equations had very similar goodness of fit statistics (Table 30). Prediction biases for pen mean live weight and within-pen SD and CV in live weight were generally different between the two equations; however, neither equation had a consistently more positive or negative bias. For both equations, prediction biases for within-pen SD and CV in live weight were generally negative, with the exception of a few weeks such as weeks 10 and 24 post-weaning.

In theory, if each parameter in an unbiased equation was allowed to be specifically fitted to each individual pig's growth curve, it should allow for exact prediction of the within-pen variation in live weight. However, the two equations used in these analyses only included random effects for 2 of the 3 parameters, as shown below, because it is not possible to fit an equation with 3 random effects with the statistical software used in this analysis (Schinckel et al., 2009a).

Bridges equation: $BW_{it} = W_0+(W_m+w_i)*(1-\exp(-\exp(k+k_i)*t^a)) + e_{it}$

GMM equation: $BW_{it} = (W_0*(k+k_i)^a+(W_m+w_i)*t^a)/((k+k_i)^a+t^a) + e_{it}$

Where: BW_{it} is the body weight of the i^{th} pig at t days of age, W_0 is the actual birth weight of each pig, parameter W_m is the upper asymptote (i.e., an estimate of mature live weight), parameters k and a are constants, parameter w_i is the random effect of the i^{th} pig on W_m, parameter k_i is the random effect of the i^{th} pig on k, e_{it} is the error term, and t is the days of age.

As a result, the goodness of fit for the individual pig growth curves developed using these equations will not be as accurate as potentially possible if all of the parameters in the equations could a random effect for each pig. More recently, Schinckel et al. (2009a) allowed the third parameter in nonlinear growth equations such as the Bridges and GMM equations to vary linearly as a function of the random effect for the upper asymptote (w_i). For example, in the current analysis, the parameter "a" in both equations would be replaced with "$a+b*w_i$", where b is the rate of increase in a as w_i increases. Including this additional parameter "b" in the equations should result in improved goodness of fit when using data from individual pigs. Unfortunately, several attempts were made to fit the equations with the additional parameter b, but with the statistical software used in this analysis, no solution could be found.

In addition, the two growth equations used in this analysis did not produce unbiased predictions of live weight (Table 31). For a number of the weigh periods, both equations had prediction biases for the pen mean live weights for barrows and gilts that were different ($P \leq 0.05$) from zero (Table 31). One major factor that might influence the goodness of fit of the equations is the environment in which the pigs are reared. In the study used for the current analysis, the pigs were given floor spaces of 0.28 and 0.59 m^2/pig from weaning to week 10 post-weaning and from week 10 post-weaning to the end of test, respectively. Previous research carried out in similar facilities would suggest that growth rate is likely to be reduced at such floor spaces (Wolter et al., 2002, Wolter et al., 2003; Peterson, 2004; Shull et al., 2012). In addition, Wolter et al. (2003) showed an improvement in ADG in the grow-finish period subsequent to a period of floor space restriction in the nursery period. Therefore, compared to growth rates of pigs in an unlimited environment, growth rates in the current study were likely to be reduced just prior to week 10 post-weaning due to a floor space restriction, increased for a few weeks after week 10 post-weaning due to the removal of the restriction, and then reduced towards the end of the study due to another floor space restriction at heavier weights. This fluctuation in growth rate can obviously cause problems in relation to developing an equation that accurately describes the growth under such conditions and is illustrated in the current analysis as the pattern in which the prediction biases for pen mean live weight fluctuated generally coincided with the these restrictions in floor space (Table 31). However, reduced floor space has been shown to have no impact on within-pen variation in live weight (Shull, 2010), suggesting that the growth of each pig in the pen is reduced to a similar degree as floor space is decreased. Therefore, the fluctuations in growth rate that occurred in the current study should have a minimal impact on the predictions of within-pen variation in live weight.

One factor that may influence accuracy of the equations at predicting the growth of individual pigs within a pen is the fact that the live weights collected on the lightest pigs in the pen after the heaviest pigs had already been removed for harvest were included in the data set. A number of studies have shown that removing a proportion of the heaviest pigs from pens increases the growth rate of the remaining pigs in the pen (Bates and Newcomb, 1997; Woodworth et al., 2000; DeDecker et al., 2005). This increase in growth rate during late finishing for the lighter pigs in the pen would shift the individual pig growth curve upwards for the lightest pigs in the pen and have a negative impact on the goodness of fit. However, when fitting nonlinear growth equations like the ones used in the current analysis, in order to get the statistical model to converge, it is necessary to obtain as many data points above the period in which maximal ADG is achieved as possible. It is for this reason that the data collected from the lighter pigs after the heaviest pigs were removed from the pens was included in the data set. Ideally, the pen of pigs would have been left intact until the lightest pigs reached the target end live weight.

Some of the difference between the predicted and actual within-pen variation in the current analysis may also be due to residual error for the equations between live weight and days on test. Assuming the residuals are independent and have a mean of zero, when random effects are fitted for individual pigs, the residual error is a measure of the variation around the prediction of an individual pig and not the variation between pigs. However, in the current analysis, the residuals within a pen did not necessarily have a mean of zero and, also, there was no way to nest individual pigs within pens in the PROC NLMIXED procedure of SAS used to develop the growth equations. In addition, it has been documented that body weight measures taken on the same individual animal are not independent and that equations developed using these data have serial correlated residual errors (Wang and Zuidof, 2004). Therefore, these violations of the assumptions of residuals may be influencing the accuracy of the equations to predict the within-pen variation in live weight. Recently, Strathe et al. (2010) proposed a multi-level nonlinear mixed effect model using data from a total of 40 pigs that included the random effect of pig nested within the random effect of litter and also accounted for the serial correlation in the residual errors. Future attempts at developing equations based on individual pig data to predict the within-pen variation in live weight should investigate this approach. However, it should be noted that with large data sets, as was the case in the current analysis, the difficulty and computation time required to obtain solutions to the equations is significant and with even more complicated models may not be practical.

CONCLUSIONS

The results of this analysis suggest that the increase in mean live weight over time for pens of pigs reared to heavy live weights in commercial conditions can be accurately described by a number of nonlinear equations. However, developing nonlinear growth equations can be complex and may not be necessary as these results suggest that growth performance can be described at least as accurately by simple polynomial or logarithmic equations between period growth performance measures and period mean live weight. Predictions of within-pen variation developed using mixed models with random effects for individual pigs were generally inaccurate and lower than the actual within-pen variation, and therefore, alternative approaches for modeling within-pen variation should be considered.

LITERATURE CITED

Bates, R. O., and M. D. Newcomb. 1997. Removal of market ready pen mates improved growth rate of remaining pigs. J. Anim. Sci. 78(Suppl. 2): 34. (Abstr.)

Bertalanffy, L. von. 1957. Quantitative laws for metabolism and growth. Quart. Rev. Biol. 32:217-232.

Bridges, T. C., U. W. Turner, E. M. Smith, T. S. Stahly, and O. J. Loewer. 1986. A mathematical procedure for estimating animal growth and body composition. Trans. ASAE. 29:1342-1347.

Craig, B. A. and A. P. Schinckel. 2001. Nonlinear mixed effects model for swine growth. Prof. Anim. Sci. 17:256-260.

DeDecker, J. M., M. Ellis, B. F. Wolter, B. P. Corrigan, S. E. Curtis, E. N. Parr, and D. M. Webel. 2005. Effects of proportion of pigs removed from a group and subsequent floor space on growth performance of finishing pigs. J. Anim. Sci. 83:449-454.

Gompertz, B. 1825. On nature of the equation expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Phil. Trans. Roy. Soc. 115:513-585.

Kebreab, E., M. Schulin-Zeuthen, S. Lopez, J. Soler, R. S. Dias, C. F. M. de Lange, and J. France. 2007. Comparative evaluation of mathematical equations to describe growth and efficiency of phosphorous utilization in growing pigs. J. Anim. Sci. 85:2498-2507.

Lopez, S., J. France, W. J. Gerrits, M. S. Dhanoa, D. J. Humphries, and J. Dijkstra. 2000. A generalized Michaelis-Menten equation for the analysis of growth. J. Anim. Sci. 78:1816-1828.

NRC. 1998. Nutrient Requirements of Swine (10^{th} Ed.). National Academy Press. Washington, DC.

Peterson, B. A. 2004. The effects of swine sire line, floor space, and gender on the growth performance and carcass characteristics and meat quality characteristics of pigs. M. S. thesis, University of Illinois, Urbana (51 pages).

Quiniou, N., S. Dubois, and J. Noblet. 2000. Voluntary feed intake and feeding behavior of group housed pigs are effected by ambient temperature and body weight. Livest. Prod. Sci. 63:245-253.

Richards, F. J. 1959. A flexible growth equation for empirical use. J. Exp. Bot. 10:290-300.

Robertson, T. B. 1908. On the normal growth rate of an individual and its biochemical significance. Archiv f ür Entwicklungsmechanik der Organismen 25:581-614.

Schinckel, A. P., N. Li, P. V. Preckel, M. E. Einstein, and D. Miller. 2003. Development of a stochastic pig compositional growth model. Prof. Anim. Sci. 19:255-260.

Schinckel, A. P., M. E. Einstein, S. Jungst, C. Booher, and S. Newman. 2009a. Evaluation of different mixed model nonlinear functions to describe the body weight growth of pigs of different sire and dam lines. Prof. Anim. Sci. 25:307-324.

Schinckel, A. P., M. E. Einstein, S. Jungst, C. Booher, and S. Newman. 2009b. Evaluation of different mixed model nonlinear functions to describe the feed intakes of pigs of different sire and dam lines. Prof. Anim. Sci. 25:345-359.

Schinckel, A. P., S. Pence, M. E. Einstein, R. Hinson, P. V. Preckel, J. S. Radcliffe, and B. T. Richert. 2006. Evaluation of different mixed model nonlinear equations on pigs fed low-nutrient excretion diets. Prof. Anim. Sci. 22:401-412.

Shull, C. M. 2010. Effect of floor space in the nursery and grow-finish periods on the growth performance of pigs. MS Thesis. University of Illinois, Urbana.

Shull, C.M., M. Ellis, B.A. Peterson, B.F. Wolter, and C.M. Peterson. 2012. Impact of the combination of floor and feeder space in the nursery and of grow-finish floor space on the wean-to-finish growth performance and carcass characteristics of pigs in a commercial facility. Page 57 in Proceedings of the 2012 Midwest Animal Science Meetings, Des Moines, IA. (Abstr).

Strathe, A. B., A. Danfaer, H. Sorensen, and E. Kebreab. 2010. A multilevel nonlinear mixed-effects approach to model growth in pigs. J. Anim. Sci. 88:638-649.

Wang, Z., and M. J. Zuidhof. 2004. Estimation of growth parameters using a nonlinear mixed Gompertz model. Poult. Sci. 83:847-852.

Whittemore, C. T. 1983. Development of recommended energy and protein allowances for growing pigs. Agric. Syst. 11:156-186.

Whittemore, C. T., D. M. Green, and P. W. Knap. 2001. Technical review of the energy and protein requirements of growing pigs: food intake. Anim. Sci. 73:3-17.

Woodworth, J. C., S. S. Dritz, M. D. Tokach, R. D. Goodband, and J. L. Nelssen. 2000. Examination of the interactive effects of stocking density and marketing strategies in a commercial production environment. J. Anim. Sci. 78(Suppl. 2):56. (Abstr.)

Wolter, B. F., M. Ellis, B. P. Corrigan, J. M. DeDecker, S. E. Curtis, E. N. Parr, and D. M. Webel. 2003. Impact of early postweaning growth rate as affected by diet complexity and space allocation on subsequent growth performance of pigs in a wean-to-finish production system. J. Anim. Sci. 81:353-359.

Wolter, B. F., M. Ellis, J. M. DeDecker, S. E. Curtis, G. R. Hollis, R. D. Shanks, E. N. Parr, and D. M. Webel. 2002. Effects of double stocking and weighing frequency on pig performance in wean-to-finish production systems. J. Anim. Sci. 80:1442-1450.

TABLES

Table 19. Summary of growth equations.

Equation name	Reference	Equation[1]
Logistic	Robertson (1908)	$W_m/(1+a*\exp(-k*t))$
von Bertalanffy	Bertalanffy (1957)	$W_m*(1-a*\exp(-k*t))^3$
Gompertz	Gompertz (1825)	$W_m*\exp(-a*\exp(-k*t))$
Richards	Richards (1959)	$W_0*W_m/(W_0^a+(W_m^a-W_0^a)*\exp(-k*t))^{1/a}$
Generalized Michaelis-Menten (GMM)	Lopez et al. (2000)	$(W_0*k^a+W_m*t^a)/(k^a+t^a)$
Bridges	Bridges et al. (1986)	$W_0+W_m*(1-\exp(-\exp(k)*t^a))$
Polynomial	N/A	$W_0+b_1*t+b_2*t^2+b_3*t^3$

[1] W_0 is the actual initial live weight, parameter W_m is the upper asymptote (i.e., an estimate of mature live weight), parameters k and a are constants that determine the shape of the curve, parameters b_1, b_2, and b_3 are coefficients for the polynomial equation, and t is days on test.

Table 20. Least-squares means for the effect of gender on growth performance from the study reported in Chapter 2 (data set 1).

Item	Gender		SEM	*P*-value
	Barrows	Gilts		
Number of observations	6	6	-	-
Body weight, kg				
Start (weaning)	5.7	5.7	0.15	0.21
Week 2	8.7	8.8	0.29	0.45
Week 4	13.6	13.8	0.37	0.44
Week 6	21.3	21.5	0.46	0.47
Week 8	31.6	32.0	0.71	0.38
Week 10	44.5	44.5	0.94	0.92
Week 12	59.8	58.7	1.26	0.22
Week 14	76.3	74.0	1.61	0.04
Week 16	92.6	89.5	1.60	0.03
Week 18	108.2	104.4	1.53	0.01
Week 20	123.8	118.7	1.74	0.01
Week 22	136.6	131.6	1.75	0.004
Week 24	149.1	144.5	1.91	0.003
End of study	167.8	167.2	1.40	0.79
Average daily gain, kg				
Start - week 2	0.24	0.24	0.015	0.46
Week 2 - week 4	0.35	0.36	0.009	0.64
Week 4 - week 6	0.55	0.55	0.013	0.53
Week 6 - week 8	0.74	0.74	0.022	0.89
Week 8 - week 10	0.92	0.89	0.018	0.06
Week 10 - week 12	1.09	1.02	0.026	0.01
Week 12 - week 14	1.17	1.09	0.030	0.001
Week 14 - week 16	1.17	1.11	0.020	0.09
Week 16 - week 18	1.12	1.06	0.018	0.04
Week 18 - week 20	1.11	1.03	0.027	0.01
Week 20 - week 22	0.91	0.92	0.025	0.82
Week 22 - week 24	0.90	0.90	0.019	0.92
Week 24 - end of study	0.83	0.82	0.025	0.95
Start - end of study	0.84	0.81	0.014	0.04
Average daily feed intake, kg				
Start - week 2	0.29	0.29	0.021	0.81
Week 2 - week 4	0.53	0.55	0.012	0.10
Week 4 - week 6	0.88	0.91	0.018	0.21
Week 6 - week 8	1.33	1.36	0.030	0.38
Week 8 - week 10	1.83	1.78	0.037	0.10
Week 10 - week 12	2.47	2.26	0.047	0.01
Week 12 - week 14	2.97	2.64	0.067	0.001
Week 14 - week 16	3.23	2.89	0.034	0.001
Week 16 - week 18	3.40	3.06	0.024	<0.001
Week 18 - week 20	3.50	3.16	0.054	0.003
Week 20 - week 22	3.34	3.16	0.039	<0.001
Week 22 - week 24	3.31	3.26	0.037	0.13
Week 24 - end of study	3.18	3.08	0.055	0.29
Start - end of study	2.36	2.24	0.018	0.001
Gain:feed, kg:kg				
Start - week 2	0.834	0.845	0.0258	0.64
Week 2 - week 4	0.666	0.656	0.0142	0.64
Week 4 - week 6	0.617	0.610	0.0057	0.48
Week 6 - week 8	0.553	0.544	0.0114	0.39
Week 8 - week 10	0.505	0.501	0.0042	0.22
Week 10 - week 12	0.443	0.450	0.0046	0.08
Week 12 - week 14	0.396	0.414	0.0049	0.03
Week 14 - week 16	0.361	0.383	0.0051	0.03
Week 16 - week 18	0.328	0.347	0.0054	0.04
Week 18 - week 20	0.318	0.325	0.0056	0.45
Week 20 - week 22	0.273	0.291	0.0069	0.13
Week 22 - week 24	0.271	0.277	0.0053	0.47
Week 24 - end of study	0.260	0.267	0.0040	0.26
Start - end of study	0.357	0.364	0.0037	0.08

Table 21. Descriptive statistics for the 181 kg live weight treatment of the study reported in Chapter 3 (data set 2).

Item	Mean	Standard Deviation	Minimum	Maximum
Number of pens	44	44	44	44
Body weight, kg				
Week 0	5.8	0.36	5.2	6.3
Week 2	8.9	0.90	7.9	10.7
Week 4	14.2	1.35	12.7	17.2
Week 6	22.0	2.27	19.0	26.6
Week 8	32.6	2.75	28.7	37.6
Week 10	45.7	3.41	40.8	51.5
Week 12	60.5	3.94	54.0	66.4
Week 14	76.7	4.20	69.4	83.3
Week 16	91.8	4.54	84.1	100.0
Week 18	107.4	4.87	97.5	115.6
Week 20	121.9	5.84	111.2	132.0
Week 22	134.8	6.15	122.7	144.6
End of study[1]	159.7	0.89	158.1	161.3
Average daily gain, kg				
Week 0 - week 2	0.23	0.030	0.17	0.28
Week 2 - week 4	0.38	0.037	0.33	0.46
Week 4 - week 6	0.56	0.075	0.45	0.70
Week 6 - week 8	0.76	0.054	0.67	0.89
Week 8 - week 10	0.94	0.085	0.72	1.08
Week 10 - week 12	1.05	0.066	0.94	1.17
Week 12 - week 14	1.15	0.099	0.94	1.31
Week 14 - week 16	1.08	0.103	0.86	1.23
Week 16 - week 18	1.11	0.080	0.96	1.26
Week 18 - week 20	1.04	0.108	0.80	1.28
Week 20 - week 22	0.91	0.067	0.78	1.00
Week 22 - end of study	0.79	0.053	0.71	0.87
Week 0 - end of study	0.83	0.035	0.78	0.90
Average daily feed intake, kg				
Week 0 - week 2	0.29	0.044	0.19	0.38
Week 2 - week 4	0.57	0.082	0.45	0.78
Week 4 - week 6	0.91	0.115	0.71	1.11
Week 6 - week 8	1.33	0.125	1.13	1.53
Week 8 - week 10	1.82	0.126	1.63	2.08
Week 10 - week 12	2.39	0.167	2.08	2.70
Week 12 - week 14	2.87	0.259	2.48	3.22
Week 14 - week 16	3.03	0.258	2.64	3.32
Week 16 - week 18	3.26	0.261	2.71	3.68
Week 18 - week 20	3.24	0.256	2.82	3.86
Week 20 - week 22	3.22	0.219	2.82	3.57
Week 22 - end of study	3.09	0.151	2.90	3.38
Week 0 - end of study	2.25	0.090	2.07	2.38
Gain:feed, kg:kg				
Week 0 - week 2	0.822	0.066	0.722	0.941
Week 2 - week 4	0.659	0.040	0.588	0.742
Week 4 - week 6	0.614	0.038	0.526	0.676
Week 6 - week 8	0.570	0.038	0.513	0.671
Week 8 - week 10	0.515	0.035	0.438	0.571
Week 10 - week 12	0.440	0.016	0.399	0.462
Week 12 - week 14	0.404	0.037	0.327	0.460
Week 14 - week 16	0.358	0.025	0.301	0.398
Week 16 - week 18	0.342	0.020	0.319	0.380
Week 18 - week 20	0.319	0.020	0.274	0.349
Week 20 - week 22	0.284	0.020	0.250	0.319
Week 22 - end of study	0.255	0.015	0.232	0.284
Week 0 - end of study	0.369	0.010	0.355	0.389

[1]End of study was immediately prior to the removal of the first pigs from the pen for harvest.

Table 22. Means from the study reported in Chapter 4 with and without morbidities and mortalities included (data set 3).

Item	Data set 3[1]	Data set 3 including data from mortalities and morbid pigs removed during the study
Live weight, kg		
Nursery period		
Start (weaning)	5.2	5.2
Week 2	8.1	8.0
Week 4	13.6	13.6
Week 6	20.6	20.6
Week 8	30.4	30.3
Week 10	42.6	42.5
Grow-finish period		
Week 10	42.8	42.7
Week 12	51.7	51.6
Week 14	68.8	68.8
Week 16	82.8	82.7
Week 18	96.6	96.5
Week 20	108.1	107.9
Week 22	119.7	119.5
Week 24	131.7	131.4
Standard deviation (within-pen), kg		
Nursery period		
Start (weaning)	1.11	1.11
Week 2	1.68	1.68
Week 4	2.78	2.81
Week 6	4.09	4.14
Week 8	5.65	5.72
Week 10	7.15	7.27
Grow-finish period		
Week 10	7.08	7.17
Week 12	8.18	8.32
Week 14	9.95	10.00
Week 16	11.20	11.32
Week 18	11.94	12.07
Week 20	12.59	12.87
Week 22	12.99	13.15
Week 24	13.39	13.54
Coefficient of variation (within-pen), %		
Nursery period		
Start (weaning)	21.36	21.39
Week 2	20.84	20.91
Week 4	20.45	20.71
Week 6	19.80	20.14
Week 8	18.57	18.89
Week 10	16.80	17.13
Grow-finish period		
Week 10	16.53	16.82
Week 12	15.82	16.12
Week 14	14.45	14.54
Week 16	13.52	13.68
Week 18	12.37	12.51
Week 20	11.64	11.93
Week 22	10.85	11.01
Week 24	10.16	10.31

[1]All mortalities and morbid pigs removed during the study were excluded from the entire data set.

Table 23. Summary of parameter estimates and measures of goodness of fit for equations between live weight and days on test.

Item	Parameter estimates[a]								R^2	RSD[b]	AIC[c]
	W_m	k	a	b_1	b_2	b_3	VAR_e	VAR_p			
Data set											
Data set 1											
Gender											
Barrows											
Equation											
Logistic	182.3	0.0277	21.225	-	-	-	5.57	0.0007	0.998	2.27	405.3
von Bertalanffy	266.9	0.0093	0.8293	-	-	-	4.28	0.0010	0.999	2.00	387.1
Gompertz	223.0	0.0140	4.1397	-	-	-	1.68	0.0009	0.999	1.25	314.6
Richards	204.0	0.0186	0.3463	-	-	-	1.23	0.0005	1.000	1.07	287.2
GMM[d]	270.3	155.89	2.1224	-	-	-	1.80	0.0010	0.999	1.28	320.2
Bridges	196.4	-9.8440	1.9749	-	-	-	1.51	0.0008	1.000	1.18	305.4
Polynomial	-	-	-	0.033	0.01013	-0.000031	2.11	0.0007	0.999	1.41	330.6
Gilts											
Equation											
Logistic	182.8	0.0262	19.466	-	-	-	6.89	0.0008	0.998	2.53	432.5
von Bertalanffy	273.5	0.0086	0.8064	-	-	-	2.90	0.0011	0.999	1.65	365.5
Gompertz	226.0	0.0131	3.9675	-	-	-	1.53	0.0010	0.999	1.20	314.7
Richards	213.4	0.0157	0.2053	-	-	-	1.40	0.0005	1.000	1.14	303.9
GMM[d]	293.4	174.57	1.9786	-	-	-	1.58	0.0010	1.000	1.21	317.1
Bridges	206.6	-9.4535	1.8672	-	-	-	1.44	0.0009	1.000	1.16	309.1
Polynomial	-	-	-	0.092	0.00882	-0.000026	1.82	0.0008	0.999	1.31	326.9
Data set 2											
Gender											
Barrows											
Equation											
Logistic	178.4	0.0286	23.124	-	-	-	5.47	0.0019	0.998	2.24	511.7
von Bertalanffy	276.8	0.0090	0.8415	-	-	-	5.04	0.0024	0.998	1.70	505.8
Gompertz	224.1	0.0140	4.2721	-	-	-	2.64	0.0023	0.999	1.57	443.0
Richards	200.8	0.0203	0.4551	-	-	-	2.85	0.0024	0.999	1.61	451.1
GMM[d]	265.8	155.06	2.1956	-	-	-	2.48	0.0026	0.999	1.51	437.7
Bridges	191.5	-10.2073	2.0529	-	-	-	2.33	0.0023	0.999	1.47	431.0
Polynomial	-	-	-	-0.038	0.01089	-0.000033	2.80	0.0021	0.999	1.61	448.0
Gilts											
Equation											
Logistic	177.3	0.0264	19.698	-	-	-	8.06	0.0013	0.997	2.73	576.2
von Bertalanffy	268.7	0.0086	0.8103	-	-	-	3.09	0.0017	0.999	1.70	480.3
Gompertz	220.8	0.0132	3.9953	-	-	-	2.39	0.0016	0.999	1.50	453.3
Richards	209.9	0.0159	0.2301	-	-	-	2.53	0.0015	0.999	1.52	459.4
GMM[d]	288.9	175.5	1.9889	-	-	-	2.09	0.0016	0.999	1.40	440.2
Bridges	202.8	-9.5124	1.8778	-	-	-	2.18	0.0015	0.999	1.43	443.9
Polynomial	-	-	-	0.072	0.00883	-0.000026	2.77	0.0014	0.999	1.61	468.0
Data sets 1 and 2 combined											
Gender											
Barrows											
Equation											
Logistic	180.1	0.0282	22.251	-	-	-	5.67	0.0014	0.998	2.24	913.8
von Bertalanffy	270.8	0.0092	0.8371	-	-	-	5.06	0.0018	0.998	2.24	897.2
Gompertz	223.1	0.0141	4.2171	-	-	-	2.46	0.0017	0.999	1.51	771.4
Richards	201.5	0.0196	0.4106	-	-	-	2.42	0.0015	0.999	1.49	767.7
GMM[d]	266.4	154.67	2.1687	-	-	-	2.46	0.0018	0.999	1.50	772.4
Bridges	193.1	-10.0549	2.0210	-	-	-	2.21	0.0016	0.999	1.43	752.2
Polynomial	-	-	-	-0.008	0.01056	-0.000032	2.73	0.0015	0.999	1.59	787.7
Gilts											
Equation											
Logistic	179.7	0.0263	19.589	-	-	-	7.55	0.0012	0.998	2.64	1001.5
von Bertalanffy	270.7	0.0086	0.8086	-	-	-	3.03	0.0015	0.999	1.68	838.5
Gompertz	223.0	0.0131	3.9830	-	-	-	2.02	0.0015	0.999	1.37	764.8
Richards	211.9	0.0158	0.2176	-	-	-	2.05	0.0013	0.999	1.37	766.3
GMM[d]	290.2	174.89	1.9853	-	-	-	1.88	0.0015	0.999	1.32	751.6
Bridges	204.2	-9.4884	1.8737	-	-	-	1.86	0.0014	0.999	1.32	749.2
Polynomial	-	-	-	0.081	0.00882	-0.000026	2.37	0.0013	0.999	1.49	791.6

[a] W_m is the upper asymptote (i.e., an estimate of mature live weight), parameters k and a are constants that determine the shape of the curve, parameters b_1, b_2, and b_3 are the coefficients for the polynomial equation, VARe is the model error term, and VARp is the variance for the random effect of pen.

[b] Residual standard deviation.

[c] Akaike's information criterion.

[d] Generalized Michaelis-Menten.

Table 24. Prediction biases for growth equations between live weight and days on test.[1]

Item	Growth equation								
	Logistic	von Bertalanffy	Gompertz	Richards	GMM[2]	Bridges	Polynomial	SEM	*P*-value
<u>Data set 1</u>									
Gender									
Barrows									
Period 1[3]									
Bias	1.09^{a}	-0.18^{cd}	-0.04^{bcd}	0.52^{ab}	-0.49^{d}	-0.22^{cd}	0.26^{bc}	0.248	<0.001
SEM	0.295	0.421	0.208	0.122	0.220	0.182	0.163	-	-
P-value	0.001	0.66	0.85	<0.001	0.03	0.24	0.12	-	-
Period 2[3]									
Bias	-1.48^{d}	0.11^{ab}	-0.14^{abc}	-0.55^{bcd}	0.22^{a}	-0.14^{abc}	-0.71^{cd}	0.286	0.01
SEM	0.442	0.311	0.257	0.171	0.237	0.241	0.263	-	-
P-value	0.004	0.74	0.60	0.01	0.37	0.57	0.02	-	-
Period 3[3]									
Bias	0.46	-0.40	-0.11	0.12	-0.19	-0.06	0.06	0.304	0.57
SEM	0.441	0.328	0.252	0.237	0.247	0.249	0.321	-	-
P-value	0.30	0.23	0.67	0.62	0.45	0.82	0.86	-	-
Gilts									
Period 1[3]									
Bias	1.26^{a}	-0.02^{ab}	0.14^{cd}	0.56^{ab}	-0.27^{d}	-0.07^{cd}	0.36^{bc}	0.242	<0.001
SEM	0.381	0.345	0.186	0.104	0.206	0.182	0.153	-	-
P-value	0.002	0.96	0.46	<0.001	0.20	0.70	0.02	-	-
Period 2[3]									
Bias	-1.59	-0.22	-0.40	-0.57	-0.05	-0.31	-0.85	0.308	0.08
SEM	0.447	0.298	0.287	0.245	0.270	0.275	0.292	-	-
P-value	0.002	0.47	0.18	0.03	0.84	0.28	0.01	-	-
Period 3[3]									
Bias	0.62	-0.18	0.07	0.18	-0.08	0.04	0.24	0.280	0.75
SEM	0.453	0.263	0.223	0.246	0.224	0.220	0.258	-	-
P-value	0.18	0.51	0.75	0.47	0.73	0.86	0.36	-	-
<u>Data set 2</u>									
Gender									
Barrows									
Period 1[3]									
Bias	0.95^{a}	0.07^{ab}	0.12^{b}	0.82^{a}	-0.20^{b}	0.02^{b}	0.26^{b}	0.259	0.002
SEM	0.258	0.393	0.251	0.176	0.241	0.216	0.226	-	-
P-value	0.001	0.85	0.63	<0.001	0.42	0.94	0.26	-	-
Period 2[3]									
Bias	-1.06	-0.48	-0.42	-0.65	-0.16	-0.40	-0.71	0.342	0.65
SEM	0.485	0.310	0.297	0.354	0.292	0.304	0.313	-	-
P-value	0.04	0.14	0.17	0.08	0.58	0.20	0.03	-	-
Period 3[3]									
Bias	0.34	-0.28	-0.08	0.12	-0.14	-0.02	0.05	0.297	0.85
SEM	0.396	0.325	0.253	0.289	0.250	0.253	0.286	-	-
P-value	0.40	0.40	0.76	0.69	0.59	0.93	0.86	-	-
Gilts									
Period 1[3]									
Bias	1.22^{a}	0.20^{bc}	0.30^{bc}	0.88^{ab}	0.07^{c}	0.27^{c}	0.54^{abc}	0.266	0.05
SEM	0.379	0.317	0.234	0.206	0.237	0.225	0.214	-	-
P-value	0.002	0.53	0.20	<0.001	0.76	0.24	0.02	-	-
Period 2[3]									
Bias	-1.40	-0.49	-0.54	-0.74	-0.32	-0.53	-0.97	0.295	0.35
SEM	0.469	0.238	0.272	0.259	0.242	0.251	0.268	-	-
P-value	0.01	0.05	0.06	0.01	0.20	0.04	0.001	-	-
Period 3[3]									
Bias	0.51	-0.11	0.08	0.17	-0.04	0.06	0.24	0.268	0.87
SEM	0.427	0.228	0.226	0.234	0.207	0.220	0.268	-	-
P-value	0.24	0.64	0.73	0.46	0.85	0.80	0.38	-	-

[a,b,c,d]Means within a row with different superscripts differ ($P \leq 0.05$).

[1]Prediction biases were calculated as the mean of the residuals (i.e., the difference between predicted values and actual values).

[2]Generalized Michaelis-Menten.

[3]Period 1 was from weaning to 60 kg live weight; period 2 was between live weights of 60 and 110 kg, and period 3 was from a 110 kg live weight to the end of study (i.e., pen mean live weights of 167.5 ± 3.30 kg and 159.7 ± 0.89 kg for data sets 1 and 2, respectively).

Table 25. Summary of parameter estimates and measures of goodness of fit for equations between live weight and growth performance measures and between cumulative feed intake and days on test.

	Parameter estimates[a]										
Item	b_0	b_1	b_2	b_3	a	b	VAR_e	VAR_p	R^2	RSD[b]	AIC[c]
Gender											
Barrows											
Polynomial equations between:											
Period ADG and period mean live weight[d,e,f]	0.0029	0.0353	-0.00032	0.00000077	-	-	0.00387	0.00079	0.96	0.061	-480.0
Period ADFI and period mean live weight[e,g,h]	-0.1625	0.0603	-0.00028	NS	-	-	0.0142	0.00045	0.99	0.116	-236.1
Period G:F and period mean live weight[e,i,j,k]	0.8356	-0.0120	0.00010	-0.00000030	-	-	0.00163	-	0.95	0.040	-660.2
Logarithmic equation between:											
Period G:F and period mean live weight[e,i,l]	-	-	-	-	1.1381	-0.1758	0.00115	0.00024	0.96	0.033	-720.5
Gilts											
Polynomial equations between:											
Period ADG and period mean live weight[d,e,f]	0.0410	0.0331	-0.00032	0.00000085	-	-	0.00574	0.00040	0.92	0.075	-433.1
Period ADFI and period mean live weight[e,g,h]	-0.1379	0.0653	-0.00041	0.00000078	-	-	0.0112	0.00040	0.99	0.103	-290.7
Period G:F and period mean live weight[e,i,j,k]	0.8305	-0.0119	0.00010	-0.00000032	-	-	0.00193	-	0.93	0.044	-655.9
Logarithmic equation between:											
Period G:F and period mean live weight[e,i,l]	-	-	-	-	1.1245	-0.1719	0.00141	0.00018	0.95	0.037	-714.2

[a]Parameters b_0,b_1, b_2, and b_3 are the coefficients for the polynomial equation ($Y=b_0+b_1*x+b_2*x^2+b_3*x^3$) and a and b are parameters for the logarithmic equation [Y=a+b*ln(x)], where Y is the dependent variable and x is the independent variable in both equations; VARe is the model error term, and VARp is the variance for the random effect of pen; "NS" = not significant ($P > 0.05$).

[b]Residual standard deviation.

[c]Akaike's information criterion.

[d]Period ADG = (total pen weight at end of period – total pen weight at start of period + weight of pigs removed during period) / (# of pigs at end of period * # of days between start and end of period + sum of all the days the pigs removed were in the pen since the start of the period).

[e]Period mean live weight = (mean live weight of pen at start of period + mean live weight of pen at end of period) / 2.

[f]Method 8 in Table 27.

[g]Period ADFI = (total feed consumed during the period) / (# of pigs at end of period * # of days between start and end of period + sum of all the days the pigs removed were in the pen since the start of the period).

[h]Method 2 in Table 28.

[i]Period G:F = Period ADG / Period ADFI.

[j]Random effect of pen was estimated as zero.

[k]Method 9 in Table 29.

[l]Method 10 in Table 29.

Table 26. Summary of parameter estimates and measures of goodness of fit for equations between cumulative feed intake and days on test.

	Gender	
Item	Barrows	Gilts
Parameter estimates[a]	-0.5266	-0.2656
b_1	0.02660	0.02171
b_2	-0.00005989	-0.00004577
b_3	0.0029	0.0353
VAR_e	25.2328	9.7673
VAR_p	0.00139	0.00198
Measures of goodness of fit		
R^2	1.00	1.00
Residual standard deviation	4.81	3.01
Akaike's information criterion	1196.1	1077.9

[a]Parameters b_1, b_2, and b_3 are the coefficients for the polynomial equation ($Y=b_1*x+b_2*x^2+b_3*x^3$); VAR_p is the variance for the random effect of pen; VAR_e is the model error term.

Table 27. Prediction biases for different methods of predicting average daily gain.[1]

	Prediction method[2]									
Item	1	2	3	4	5	6	7	8	SEM	*P*-value
Gender										
Barrows										
Period 1[3]										
Bias	-0.05[d]	0.07[a]	0.04[b]	-0.01[c]	0.01[c]	0.00[c]	0.00[c]	0.00[c]	0.007	<0.001
SEM	0.006	0.008	0.005	0.005	0.009	0.008	0.008	0.003	-	-
P-value	<0.001	<0.001	<0.001	0.26	0.34	0.56	0.65	0.69	-	-
Period 2[3]										
Bias	0.07[a]	-0.07[d]	-0.03[c]	0.01[b]	-0.03[c]	-0.02[bc]	-0.03[c]	0.01[b]	0.010	<0.001
SEM	0.013	0.010	0.010	0.011	0.010	0.010	0.011	0.009	-	-
P-value	<0.001	<0.001	0.01	0.34	0.005	0.08	0.03	0.35	-	-
Period 3[3]										
Bias	-0.05[c]	0.06[a]	0.02[ab]	0.00[bc]	0.03[ab]	0.01[b]	0.02[b]	0.00[bc]	0.014	0.003
SEM	0.019	0.014	0.013	0.013	0.013	0.013	0.016	0.012	-	-
P-value	0.01	<0.001	0.06	0.75	0.05	0.32	0.35	0.73	-	-
Gilts										
Period 1[3]										
Bias	-0.07[d]	0.06[a]	0.02[b]	-0.01[c]	0.01[bc]	0.00[bc]	0.00[c]	0.00[c]	0.006	<0.001
SEM	0.008	0.007	0.005	0.006	0.007	0.006	0.006	0.005	-	-
P-value	<0.001	<0.001	0.002	0.29	0.45	0.70	0.61	0.82	-	-
Period 2[3]										
Bias	0.07[a]	-0.05[c]	-0.01[b]	0.01[b]	-0.02[bc]	-0.01[bc]	-0.01[b]	0.01[b]	0.012	<0.001
SEM	0.015	0.012	0.012	0.012	0.011	0.012	0.012	0.010	-	-
P-value	<0.001	<0.001	0.60	0.48	0.06	0.22	0.44	0.29	-	-
Period 3[3]										
Bias	-0.05[c]	0.04[a]	0.01[ab]	0.00[b]	0.02[ab]	0.01[ab]	0.00[ab]	-0.01[b]	0.014	0.01
SEM	0.020	0.013	0.013	0.013	0.013	0.013	0.015	0.013	-	-
P-value	0.01	0.003	0.55	0.81	0.10	0.38	0.82	0.65	-	-

[a,b,c,d]Means within a row with different superscripts differ ($P \leq 0.05$).

[1]Prediction biases were calculated as the mean of the differences between predicted values and actual period ADG.

[2]Methods 1 to 7 used the derivatives of the Logistic, von Bertalanffy, Gompertz, Richards, Generalized Michaelis-Menten, Bridges, and Polynomial equations between live weight and days on test, respectively; Method 8 was using a polynomial equation between period ADG and period mean live weight.

[3]Period 1 was from weaning to a period mean live weight of 60 kg; period 2 was between period mean live weights of 60 and 110 kg, and period 3 was from a period mean live weight of 110 kg to the end of study (i.e., a period mean live weight of 158.3 ± 4.58 kg).

Table 28. Prediction biases for different methods of predicting average daily feed intake.[a]

Item	Prediction method[b] 1	2	SEM	*P*-value
Gender				
Barrows				
Period 1[c]				
Bias	0.07	0.01	0.022	0.05
SEM	0.031	0.007	-	-
P-value	0.03	0.38	-	-
Period 2[c]				
Bias	-0.18	-0.03	0.018	<0.001
SEM	0.018	0.018	-	-
P-value	<0.001	0.12	-	-
Period 3[c]				
Bias	0.09	0.01	0.024	0.02
SEM	0.026	0.020	-	-
P-value	0.001	0.58	-	-
Gilts				
Period 1[c]				
Bias	0.03	0.00	0.013	0.08
SEM	0.017	0.006	-	-
P-value	0.07	0.99	-	-
Period 2[c]				
Bias	-0.09	0.00	0.014	<0.001
SEM	0.013	0.014	-	-
P-value	<0.001	0.75	-	-
Period 3[c]				
Bias	0.04	0.00	0.020	0.09
SEM	0.021	0.019	-	-
P-value	0.04	0.87	-	-

[a]Prediction biases were calculated as the mean of the differences between the predicted values and actual period ADFI.

[b]Method 1 was using the derivative of a polynomial equation between cumulative feed intake and days on test; Method 2 was using a polynomial equation between period ADFI and period mean live weight.

[c]Period 1 was from weaning to a period mean live weight of 60 kg; period 2 was between period mean live weights of 60 and 110 kg, and period 3 was from a period mean live weight of 110 kg to the end of study (i.e., a period mean live weight of 158.3 ± 4.58 kg).

Table 29. Prediction biases for different methods of predicting gain:feed.[1]

	Prediction method[2]											
Item	1	2	3	4	5	6	7	8	9	10	SEM	*P*-value
Gender												
Barrows												
Period 1[3]												
Bias	-0.029[e]	0.105[a]	0.056[b]	0.014[c]	-0.058[e]	-0.044[e]	-0.031[de]	0.000[cd]	0.001[cd]	0.000[cd]	0.0125	<0.001
SEM	0.0075	0.0124	0.0085	0.0069	0.0219	0.0187	0.0177	0.0047	0.0060	0.0049	-	-
P-value	<0.001	<0.001	<0.001	0.04	0.01	0.02	0.09	0.96	0.84	0.93	-	-
Period 2[3]												
Bias	0.024[a]	-0.019[d]	-0.005[c]	0.007[b]	-0.005[c]	-0.002[c]	-0.004[c]	0.007[b]	-0.007[c]	-0.002[c]	0.0026	<0.001
SEM	0.0030	0.0023	0.0024	0.0026	0.0025	0.0024	0.0025	0.0026	0.0026	0.0026	-	-
P-value	<0.001	<0.001	0.07	0.01	0.04	0.42	0.08	0.01	0.01	0.50	-	-
Period 3[3]												
Bias	-0.018[d]	0.019[a]	0.007[bc]	-0.003[c]	0.008[b]	0.003[bc]	0.003[bc]	-0.002[c]	0.003[bc]	0.002[bc]	0.0039	<0.001
SEM	0.0056	0.0042	0.0036	0.0037	0.0036	0.0037	0.0048	0.0027	0.0032	0.0028	-	-
P-value	0.003	<0.001	0.06	0.45	0.04	0.40	0.56	0.55	0.31	0.52	-	-
Gilts												
Period 1[3]												
Bias	-0.049[f]	0.090[a]	0.037[b]	0.013[c]	-0.038[ef]	-0.027[def]	-0.011[cde]	0.001[cd]	0.004[cd]	0.003[cd]	0.0107	<0.001
SEM	0.0072	0.0117	0.0083	0.0070	0.0187	0.0162	0.0117	0.0052	0.0063	0.0052	-	-
P-value	<0.001	<0.001	<0.001	0.07	0.04	0.09	0.33	0.81	0.06	0.60	-	-
Period 2[3]												
Bias	0.024[a]	-0.017[e]	-0.003[bcd]	0.002[bc]	-0.009[cde]	-0.006[bcd]	-0.005[bcd]	0.003[b]	-0.013[de]	-0.010[de]	0.0038	<0.001
SEM	0.0046	0.0037	0.0038	0.0038	0.0036	0.0037	0.0040	0.0033	0.0037	0.0035	-	-
P-value	<0.001	<0.001	0.37	0.65	0.02	0.10	0.23	0.32	0.001	0.01	-	-
Period 3[3]												
Bias	-0.017[c]	0.014[a]	0.003[b]	0.000[b]	0.007[ab]	0.004[ab]	0.001[b]	-0.001[b]	0.004[ab]	0.003[b]	0.0040	0.01
SEM	0.0063	0.0036	0.0037	0.0039	0.0035	0.0036	0.0046	0.0033	0.0036	0.0033	-	-
P-value	0.01	<0.001	0.39	0.90	0.04	0.24	0.75	0.79	0.25	0.36	-	-

[a,b,c,d,e,f]Means within a row with different superscripts differ ($P \leq 0.05$).

[1]Prediction biases were calculated as the mean of the differences between predicted values and actual period G:F.

[2]Methods 1 to 7 were dividing ADG predicted using the derivatives of the Logistic, von Bertalanffy, Gompertz, Richards, Generalized Michaelis-Menten, Bridges, and Polynomial equations between live weight and days on test, respectively, by predicted ADFI; Method 8 was dividing ADG predicted using a polynomial equation between period ADG and period mean live weight by predicted ADFI; Methods 9 and 10 were developing polynomial and logarithmic equations between period G:F and period mean live weight.

[3]Period 1 was from weaning to a period mean live weight of 60 kg; period 2 was between period mean live weights of 60 and 110 kg, and period 3 was from a period mean live weight of 110 kg to the end of study (i.e., a period mean live weight of 158.3 ± 4.58 kg).

Table 30. Parameter estimates, standard errors, and measures of goodness of fit for the Bridges and Generalized Michaelis-Menten (GMM) growth equations developed using individual pig data.

Item	Estimate	Approximate SE	R^2	RSD[a]	AIC[b]
Equation					
Bridges					
Gender					
Barrows (n=338)					
Parameters[c]					
W_m	201.23	1.6946	0.998	8.33	25,061
k	-11.5954	0.02746	-	-	-
a	2.2368	0.005752	-	-	-
Variance (e)	5.4485	0.1183	-	-	-
Variance (w_i)	639.04	61.1103	-	-	-
Variance (k_i)	0.08172	0.5850	-	-	-
Covariance (w_ik_i)	-5.7706	0.006698	-	-	-
Gilts (n=418)					
Parameters[c]					
W_m	205.25	1.7622	0.998	7.60	32,686
k	-10.9414	0.02107	-	-	-
a	2.0843	0.004516	-	-	-
Variance (e)	4.7304	0.08817	-	-	-
Variance (w_i)	930.47	78.1352	-	-	-
Variance (k_i)	0.06218	0.5417	-	-	-
Covariance (w_ik_i)	-5.8092	0.004651	-	-	-
GMM					
Gender					
Barrows (n=338)					
Parameters[c]					
W_m	283.54	2.9261	0.998	8.02	25,120
k	195.85	1.7745	-	-	-
a	2.3668	0.007685	-	-	-
Variance (e)	5.4265	0.1178	-	-	-
Variance (w_i)	1677.03	168.37	-	-	-
Variance (k_i)	860.70	87.3187	-	-	-
Covariance (w_ik_i)	686.59	54.4525	-	-	-
Gilts (n=418)					
Parameters[c]					
W_m	291.42	2.6271	0.998	7.73	32,659
k	211.58	1.6564	-	-	-
a	2.1994	0.005791	-	-	-
Variance (e)	4.6771	0.08734	-	-	-
Variance (w_i)	1700.89	117.22	-	-	-
Variance (k_i)	825.83	67.4170	-	-	-
Covariance (w_ik_i)	694.70	49.6186	-	-	-

[a]Residual standard deviation.
[b]Akaike's information criterion.
[c]W_m is the upper asymptote (i.e., an estimate of mature live weight), parameters k and a are constants that determine the shape of the curve, variance (w_i) and variance (k_i) are variance terms for the random effects of the i^{th} pig on W_m and k, respectively, and variance(e) is the model error term.

Table 31. Prediction biases for the pen mean of individual pig live weights predicted using the Bridges and Generalized Michaelis-Menten (GMM) equations.[1]

	Growth equation		Bridges = 0		GMM = 0		Bridges vs. GMM	
Item	Bridges	GMM	SEM	*P*-value	SEM	*P*-value	SEM	*P*-value
Gender								
Barrows								
Nursery period								
Start (weaning)	-1.76	-2.01	0.118	0.04	0.115	0.04	0.117	0.01
Week 2	-1.12	-1.51	0.043	0.02	0.038	0.02	0.040	0.01
Week 4	-0.70	-1.12	0.071	0.06	0.065	0.04	0.068	0.01
Week 6	0.41	0.11	0.048	0.08	0.040	0.22	0.044	0.02
Week 8	0.51	0.42	0.003	0.004	0.015	0.02	0.011	0.09
Week 10	1.86	2.02	0.878	0.28	0.860	0.26	0.870	0.07
Grow-finish period								
Week 10	1.53	1.71	0.573	0.06	0.548	0.04	0.561	0.004
Week 12	0.93	1.20	0.378	0.07	0.364	0.03	0.371	0.001
Week 14	-0.61	-0.34	0.092	0.003	0.107	0.03	0.100	<0.001
Week 16	-1.35	-1.24	0.305	0.01	0.307	0.02	0.306	0.004
Week 18	-1.43	-1.53	0.337	0.01	0.331	0.01	0.334	0.01
Week 20	0.87	0.58	0.561	0.19	0.575	0.37	0.568	<0.001
Week 22	1.58	1.24	0.415	0.02	0.406	0.04	0.411	<0.001
Week 24	0.75	0.61	0.355	0.10	0.358	0.16	0.357	0.002
Gilts								
Nursery period								
Start (weaning)	-1.27	-1.53	0.088	0.005	0.087	0.003	0.088	<0.001
Week 2	-0.41	-0.80	0.141	0.10	0.145	0.03	0.143	<0.001
Week 4	-0.07	-0.46	0.127	0.64	0.131	0.07	0.129	0.001
Week 6	0.56	0.29	0.144	0.06	0.135	0.17	0.139	0.004
Week 8	0.22	0.15	0.182	0.34	0.191	0.52	0.186	0.07
Week 10	0.33	0.47	0.476	0.57	0.463	0.41	0.470	0.02
Grow-finish period								
Week 10	0.32	0.47	0.324	0.37	0.316	0.20	0.320	<0.001
Week 12	0.68	0.92	0.308	0.08	0.311	0.03	0.309	<0.001
Week 14	-0.31	-0.01	0.227	0.24	0.233	0.95	0.230	<0.001
Week 16	-0.54	-0.33	0.130	0.01	0.141	0.07	0.136	<0.001
Week 18	-0.84	-0.79	0.278	0.03	0.281	0.04	0.279	0.12
Week 20	0.28	0.14	0.269	0.35	0.277	0.63	0.273	0.004
Week 22	1.54	1.29	0.237	0.001	0.233	0.003	0.235	<0.001
Week 24	0.38	0.14	0.314	0.28	0.308	0.67	0.311	<0.001

[1]Prediction biases were calculated as the mean of the differences between predicted values and actual values.

Table 32. Prediction biases for the within-pen standard deviation in live weight predicted using the Bridges and Generalized Michaelis-Menten (GMM) equations.[1]

	Growth equation		Bridges = 0		GMM = 0		Bridges vs. GMM	
Item	Bridges	GMM	SEM	*P*-value	SEM	*P*-value	SEM	*P*-value
Gender								
Barrows								
Nursery period								
Start (weaning)	-0.50	-0.52	0.040	0.05	0.037	0.04	0.038	0.12
Week 2	-0.46	-0.45	0.053	0.07	0.045	0.06	0.049	0.48
Week 4	-0.53	-0.45	0.057	0.07	0.044	0.06	0.051	0.11
Week 6	-0.40	-0.23	0.029	0.05	0.008	0.02	0.021	0.08
Week 8	-0.45	-0.22	0.079	0.11	0.052	0.14	0.069	0.08
Week 10	-0.19	0.04	0.112	0.34	0.081	0.74	0.098	0.09
Grow-finish period								
Week 10	-0.15	0.06	0.072	0.10	0.052	0.28	0.063	0.001
Week 12	-0.30	-0.14	0.035	0.001	0.044	0.03	0.040	0.002
Week 14	-0.48	-0.48	0.161	0.04	0.161	0.04	0.161	0.99
Week 16	-0.54	-0.68	0.164	0.03	0.166	0.01	0.165	<0.001
Week 18	-0.43	-0.66	0.074	0.004	0.067	0.001	0.070	0.001
Week 20	-0.20	-0.41	0.108	0.14	0.077	0.01	0.094	0.004
Week 22	-0.01	-0.08	0.092	0.88	0.121	0.55	0.107	0.19
Week 24	-0.40	-0.21	0.117	0.03	0.104	0.11	0.111	0.01
Gilts								
Nursery period								
Start (weaning)	-0.41	-0.43	0.056	0.02	0.052	0.01	0.054	0.06
Week 2	-0.40	-0.38	0.049	0.02	0.047	0.01	0.048	0.07
Week 4	-0.55	-0.48	0.071	0.02	0.069	0.02	0.070	0.002
Week 6	-0.72	-0.59	0.094	0.02	0.086	0.02	0.090	0.004
Week 8	-0.88	-0.69	0.132	0.02	0.121	0.03	0.127	0.01
Week 10	-0.63	-0.44	0.034	0.003	0.031	0.01	0.033	0.01
Grow-finish period								
Week 10	-0.63	-0.44	0.068	<0.001	0.062	0.001	0.065	<0.001
Week 12	-0.53	-0.37	0.080	0.001	0.074	0.004	0.077	<0.001
Week 14	-0.46	-0.39	0.071	0.001	0.068	0.002	0.070	<0.001
Week 16	-0.47	-0.50	0.091	0.004	0.092	0.003	0.092	0.003
Week 18	-0.13	-0.23	0.144	0.40	0.138	0.16	0.141	0.001
Week 20	-0.17	-0.28	0.070	0.06	0.066	0.01	0.068	0.004
Week 22	-0.12	-0.19	0.082	0.21	0.078	0.06	0.080	0.04
Week 24	0.07	0.08	0.081	0.45	0.079	0.36	0.080	0.61

[1]Prediction biases were calculated as the mean of the differences between predicted values and actual values.

Table 33. Prediction biases for the within-pen coefficient of variation in live weight predicted using the Bridges and Generalized Michaelis-Menten (GMM) equations.[1]

	Growth equation		Bridges = 0		GMM = 0		Bridges vs. GMM	
Item	Bridges	GMM	SEM	*P*-value	SEM	*P*-value	SEM	*P*-value
Gender								
Barrows								
Nursery period								
Start (weaning)	-3.14	-2.23	0.327	0.07	0.253	0.07	0.292	0.05
Week 2	-3.06	-1.82	0.558	0.11	0.454	0.16	0.509	0.05
Week 4	-2.97	-1.69	0.329	0.07	0.219	0.08	0.279	0.05
Week 6	-2.34	-1.25	0.110	0.03	0.006	0.003	0.078	0.06
Week 8	-1.81	-1.00	0.278	0.10	0.189	0.12	0.237	0.07
Week 10	-1.20	-0.76	0.107	0.06	0.172	0.14	0.143	0.09
Grow-finish period								
Week 10	-0.98	-0.55	0.255	0.02	0.242	0.08	0.249	0.003
Week 12	-0.86	-0.64	0.160	0.01	0.170	0.02	0.165	0.01
Week 14	-0.56	-0.61	0.215	0.06	0.212	0.04	0.214	0.01
Week 16	-0.42	-0.60	0.180	0.08	0.180	0.03	0.180	<0.001
Week 18	-0.25	-0.47	0.070	0.02	0.066	0.002	0.068	0.001
Week 20	-0.26	-0.42	0.077	0.03	0.057	0.002	0.068	0.01
Week 22	-0.14	-0.17	0.094	0.21	0.113	0.21	0.104	0.52
Week 24	-0.35	-0.20	0.094	0.02	0.083	0.07	0.089	0.005
Gilts								
Nursery period								
Start (weaning)	-3.85	-3.01	1.107	0.07	1.112	0.11	1.114	0.003
Week 2	-4.07	-3.07	0.765	0.03	0.809	0.06	0.787	0.004
Week 4	-3.96	-2.97	0.369	0.01	0.357	0.01	0.363	0.01
Week 6	-3.91	-3.06	0.573	0.02	0.501	0.03	0.538	0.01
Week 8	-2.99	-2.35	0.387	0.02	0.330	0.02	0.360	0.01
Week 10	-1.60	-1.21	0.269	0.03	0.248	0.04	0.259	0.01
Grow-finish period								
Week 10	-1.60	-1.21	0.241	0.001	0.224	0.003	0.233	<0.001
Week 12	-1.21	-0.97	0.147	<0.001	0.138	0.001	0.143	<0.001
Week 14	-0.61	-0.57	0.073	<0.001	0.069	<0.001	0.071	0.01
Week 16	-0.50	-0.57	0.122	0.01	0.123	0.01	0.122	0.001
Week 18	-0.04	-0.15	0.141	0.79	0.132	0.32	0.137	0.002
Week 20	-0.19	-0.28	0.083	0.07	0.081	0.02	0.082	0.01
Week 22	-0.24	-0.28	0.057	0.01	0.049	0.002	0.053	0.16
Week 24	0.02	0.05	0.056	0.69	0.056	0.39	0.056	0.19

[1]Prediction biases were calculated as the mean of the differences between predicted values and actual values.

FIGURES

Figure 22. Predicted live weight over time for barrows using various growth equations.

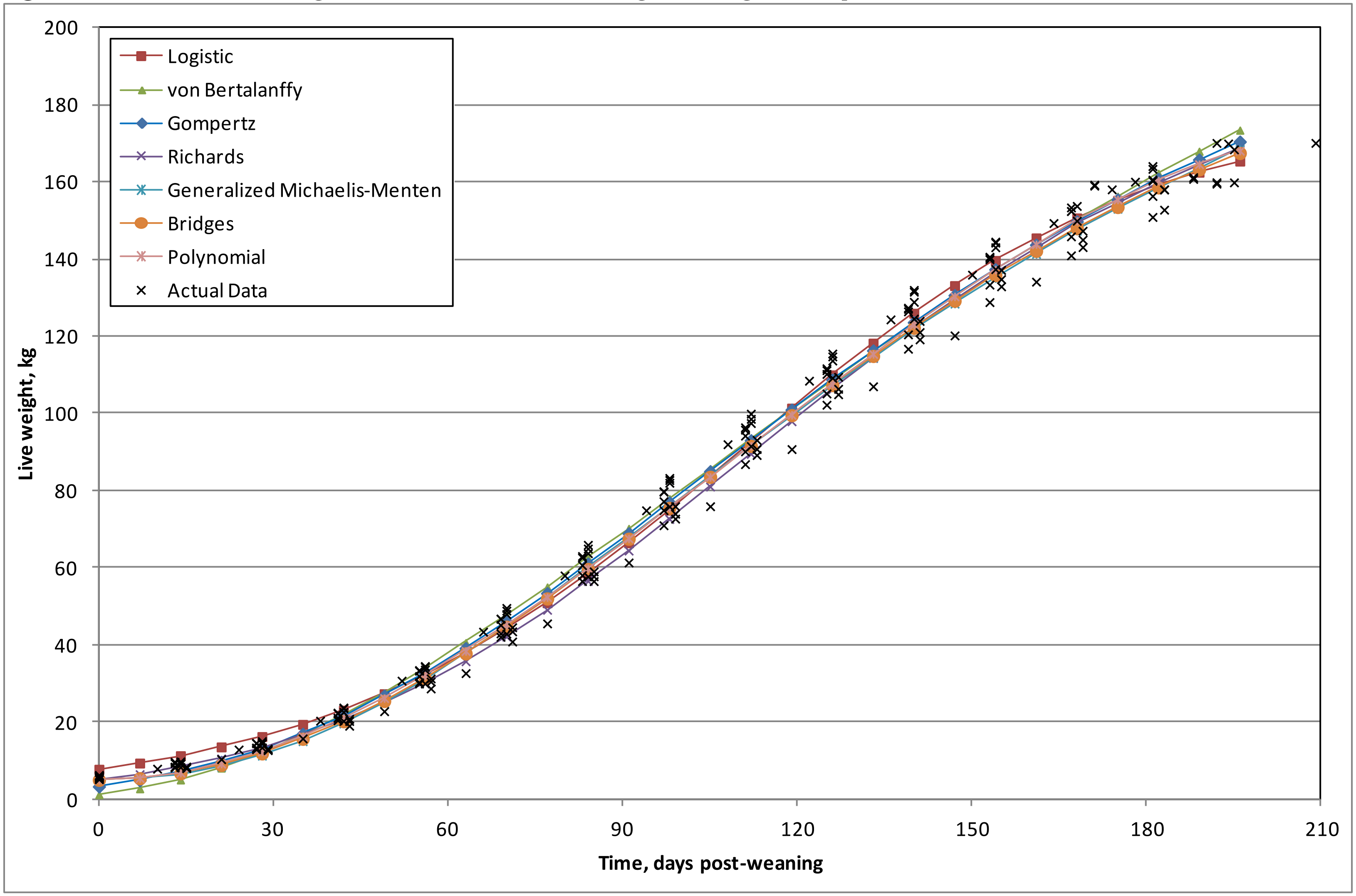


Figure 23. Predicted live weight over time for gilts using various growth equations.

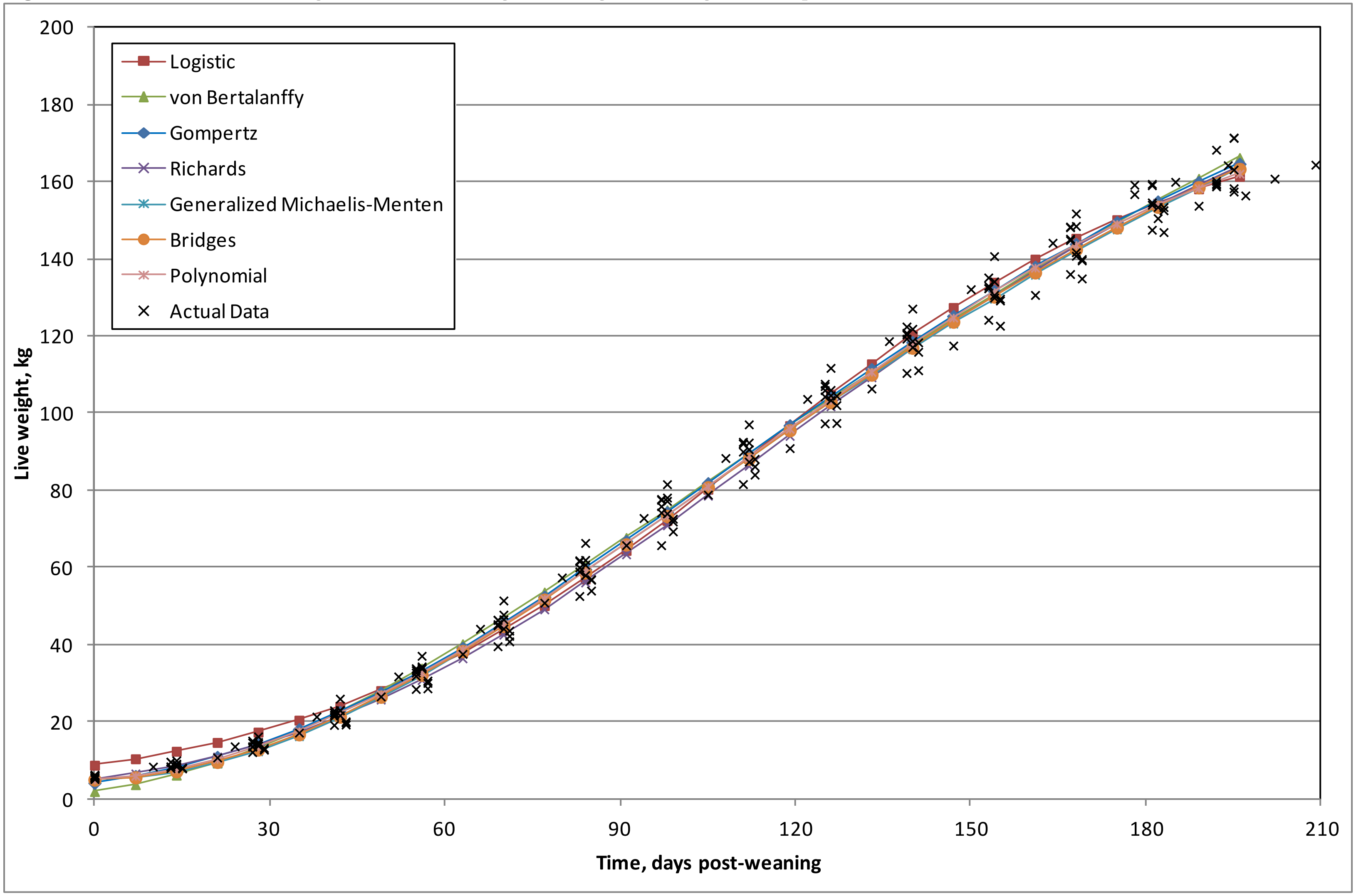


Figure 24. Predicted average daily gain over live weight for barrows.

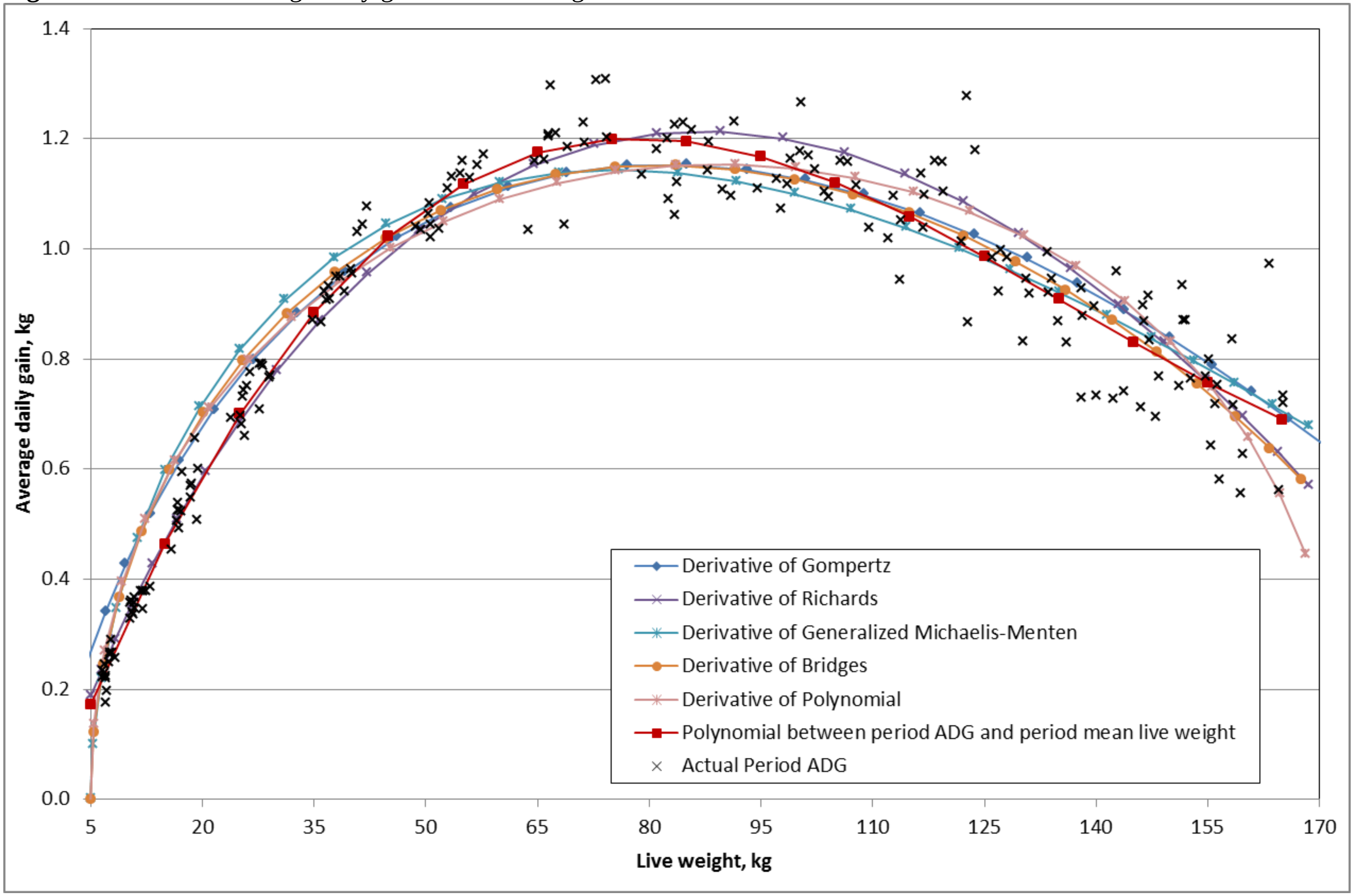


Figure 25. Predicted average daily gain over live weight for gilts.

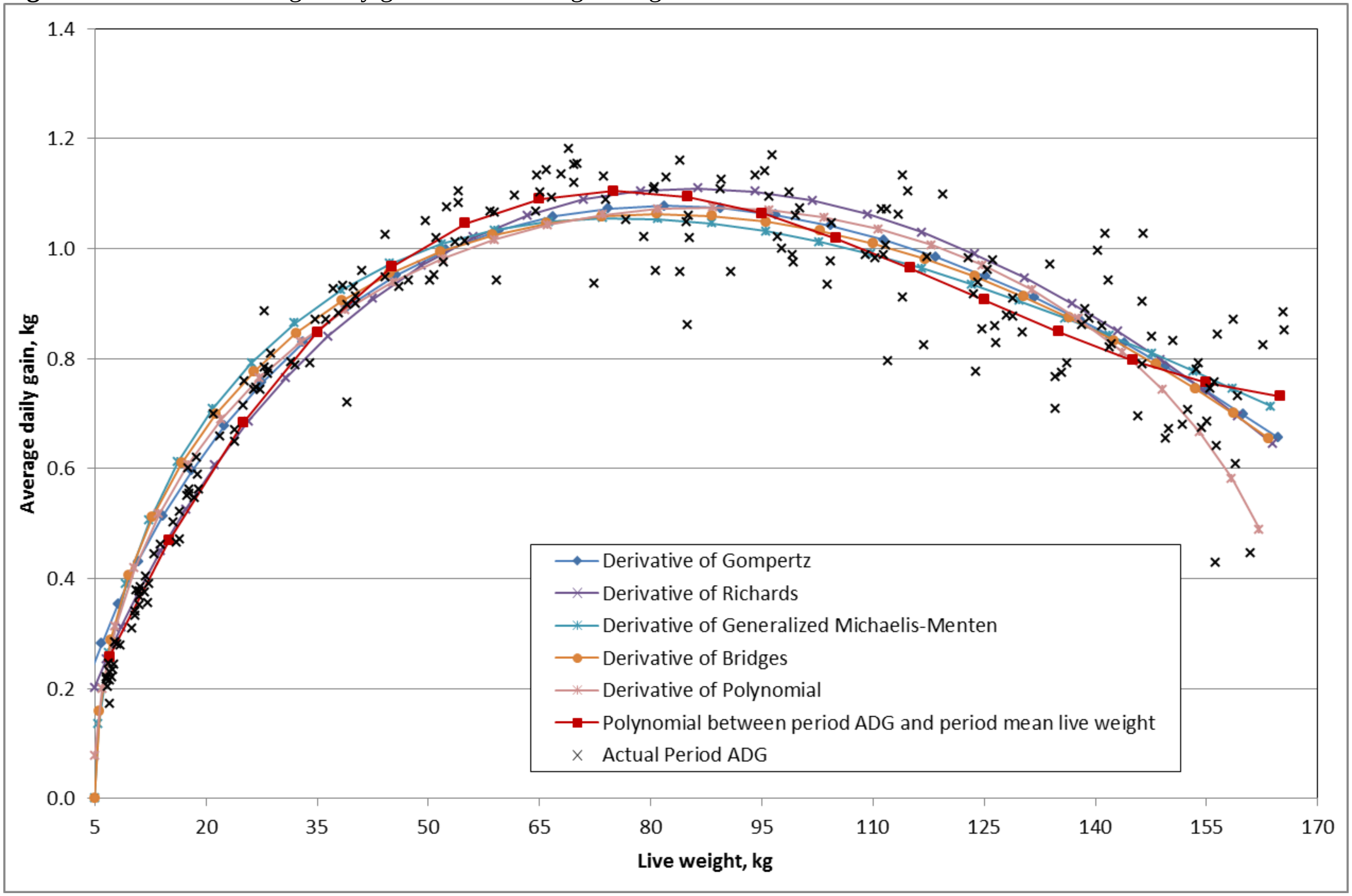
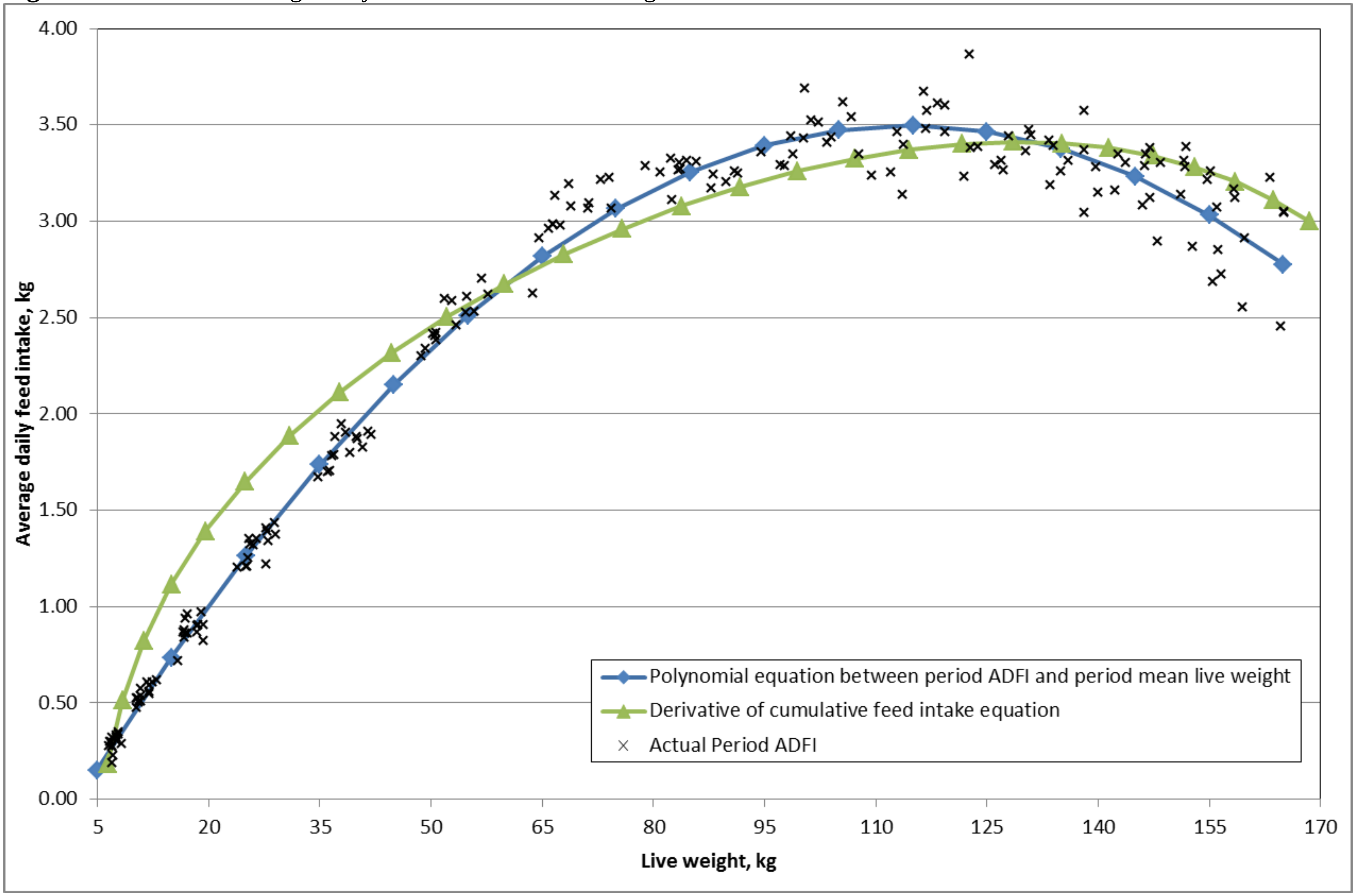
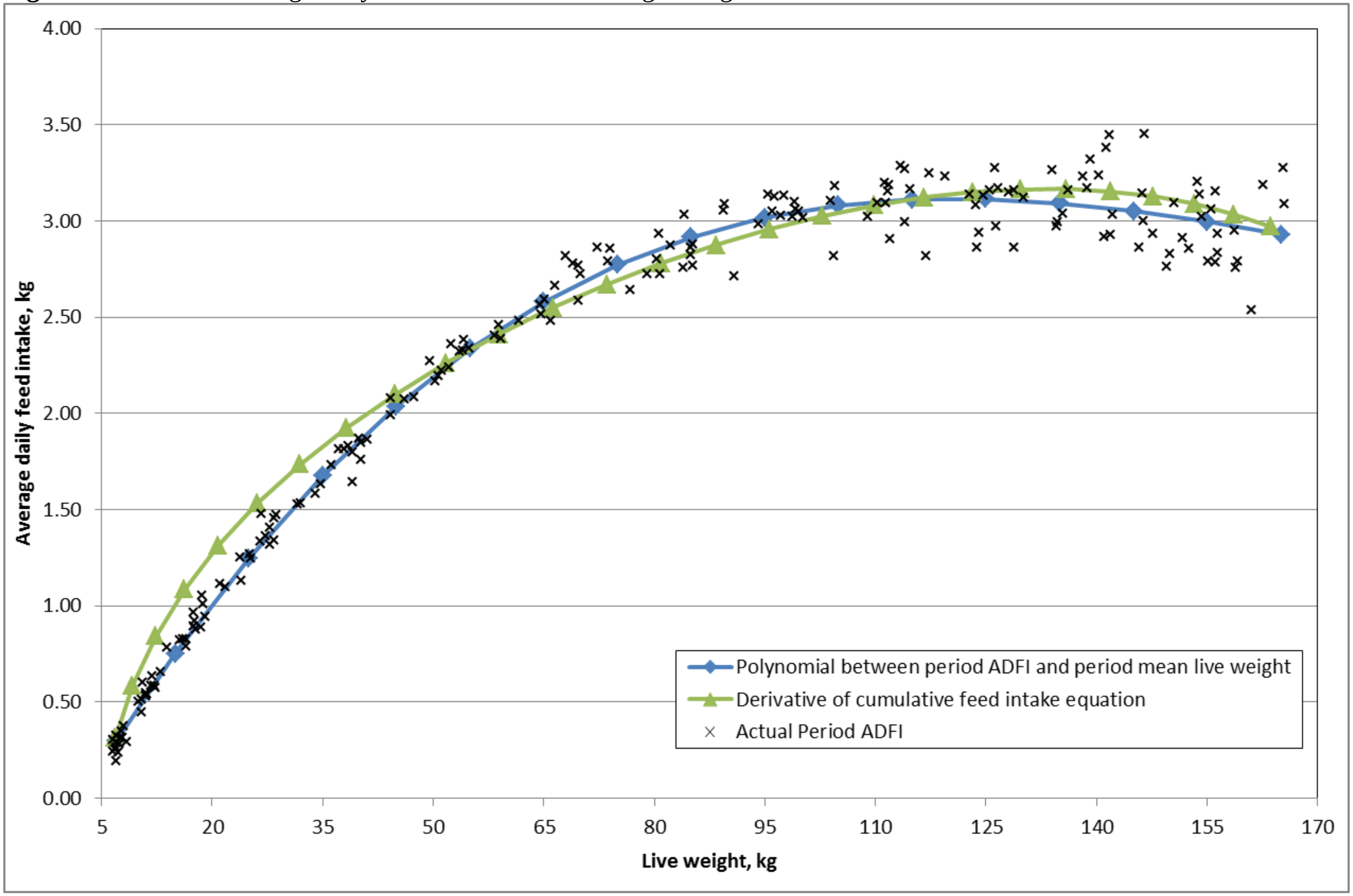


Figure 26. Predicted average daily feed intake over live weight for barrows.



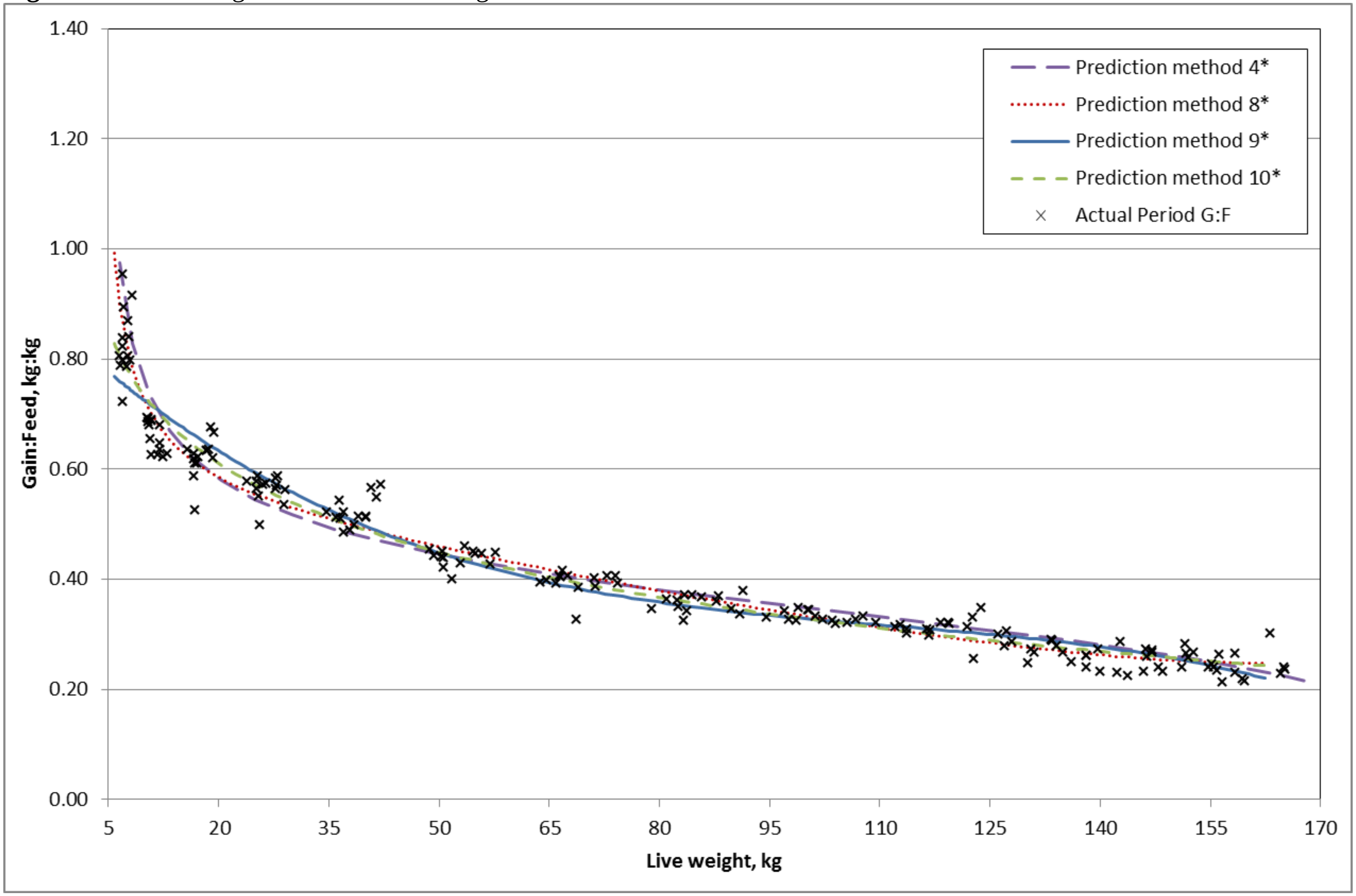
Note: ADFI predictions developed using the derivative of the equation between cumulative feed intake and days on test were plotted against the live weight predictions developed from the Bridges equation between live weight and days on test.

Figure 27. Predicted average daily feed intake over live weight for gilts.



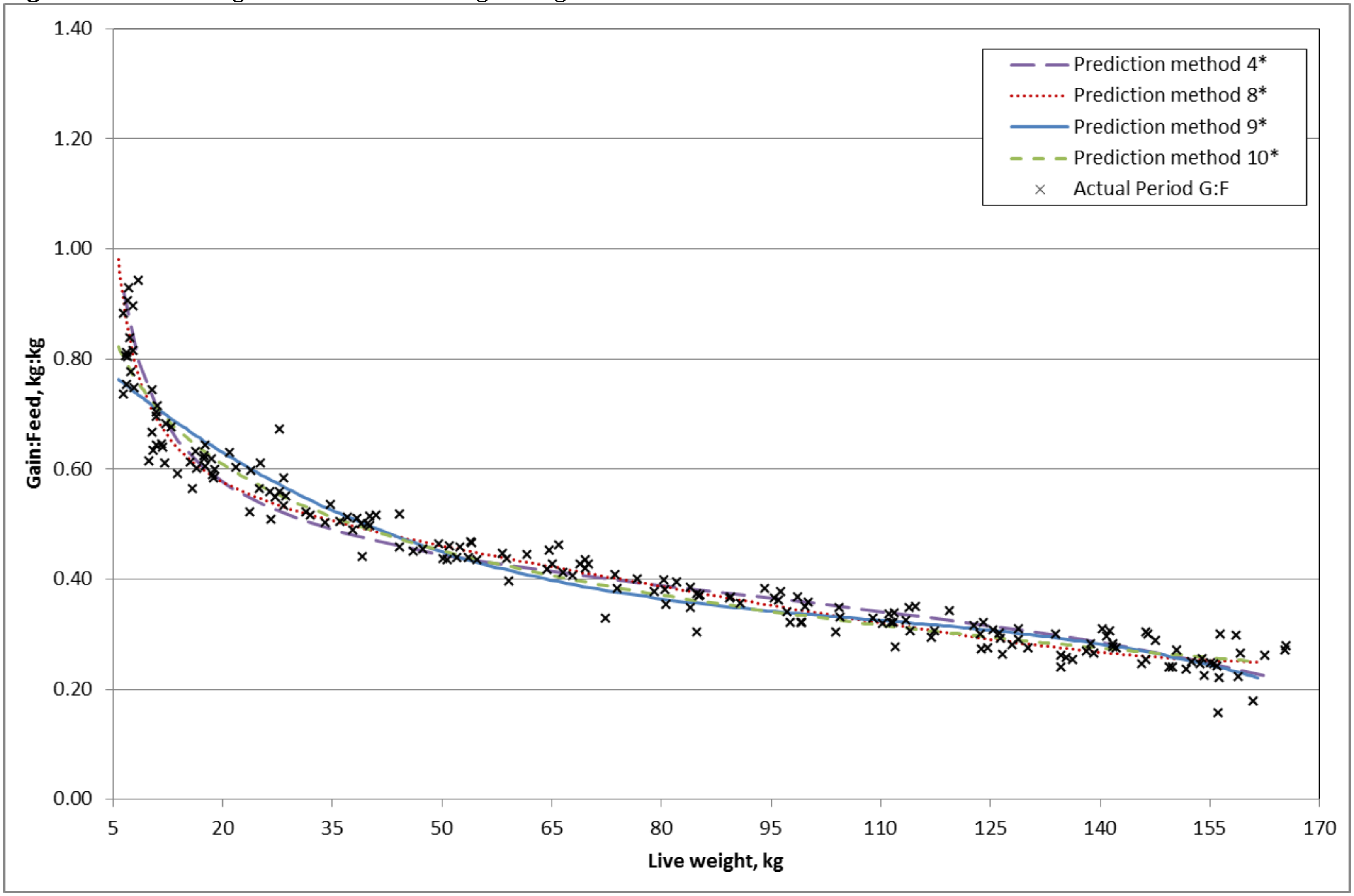
Note: ADFI predictions developed using the derivative of the equation between cumulative feed intake and days on test were plotted against the live weight predictions developed from the Bridges equation between live weight and days on test.

Figure 28. Predicted gain:feed over live weight for barrows.



*Prediction method 4 was developed by dividing ADG predicted from the derivative of the Richards equation between live weight and days on test by predicted ADFI, prediction method 8 was developed by dividing ADG predicted from the polynomial equation between period ADG and period mean live weight by predicted ADFI, and prediction methods 9 and 10 were developed from polynomial and logarithmic equations between period G:F and period mean live weight, respectively.

Figure 29. Predicted gain:feed over live weight for gilts.



*Prediction method 4 was developed by dividing ADG predicted from the derivative of the Richards equation between live weight and days on test by predicted ADFI, prediction method 8 was developed by dividing ADG predicted from the polynomial equation between period ADG and period mean live weight by predicted ADFI, and prediction methods 9 and 10 were developed from polynomial and logarithmic equations between period G:F and period mean live weight, respectively.

FUTURE PERSPECTIVES

The equations and relationships developed in this thesis were developed using a single genotype and a specific set of experimental conditions. The lean growth potential of the genetic lines will likely have a significant impact on the relationships between live weight and measures of growth performance and carcass characteristics. Other factors, such as floor and feeder space, environmental temperature, health status, and diet composition, may also impact growth performance and carcass characteristics and should be considered when interpreting the results presented in this thesis.

A model that would predict the growth performance and carcass characteristics of pigs across a range of conditions would be of significant value to a swine production system. However, developing such a model would require, firstly, a detailed understanding of which factors impact these measures, secondly, what impact each of these factors have on these measures, and thirdly, how these factors interact to impact these measures. In addition, predicting performance at a specific point in time or at a specific live weight requires not only an understanding of the overall impact of these factors but also an understanding of the instantaneous response to these factors over time or with increases in live weight. At the current point in time, knowledge is limited on how the various factors that impact the growth performance and carcass characteristics of pigs interact. In addition, the vast majority of published studies have focused primarily on the impact of various factors on overall growth performance rather than the instantaneous responses.

Developing a research program to answer all of the questions required to build a model that predicts the exact growth performance and carcass characteristics of pigs over time or live weight is highly impractical and in reality it is unlikely that an accurate, predictive model will be developed due to the inherent variation in pig performance. However, with increased focus on how future experiments are designed, growth models can be continually improved and used in both economic modeling and as a means of increasing the knowledge of swine growth.